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A Study to Determine the Nature and Extent of Ozone and Ozone Precursor Transport in Selected Areas of California

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

A STUDY TO DETERMINE THE NATURE AND EXTENT OF OZONE AND OZONE PRECURSOR TRANSPORT IN SELECTED AREAS OF CALIFORNIA

Final Report
Contract No. A932-129

Prepared for:

Research Division
California Air Resources Board
2020 L Street
Sacramento, CA 95814

Submitted by:

Sonoma Technology, Inc.
5510 Skylane Blvd.,
Suite 101
Santa Rosa, CA 95403-1083

Prepared by:

Paul T. Roberts
Stefan Musarra
Ted B. Smith
Frederick W. Lurmann

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ABSTRACT

This project was designed to assess the contribution of transported pollutants to violations of the state ozone standard within the air basins covered by this report using existing data and advanced data analysis techniques. The objectives of the project were to determine the characteristics of ozone and ozone precursor transport within the California air basins covered by this report and to identify whether the contribution of transported pollutants to ozone violations in each downwind area was inconsequential, significant, or overwhelming, relative to locally-emitted pollutants. The precursor pollutants of interest were nitrogen oxides and reactive organic gases.

This project evaluated transport to the following areas:

- The Broader Sacramento Area and the Upper Sacramento Valley.
- The North Central Coast Air Basin (NCC).
- The Southeast Desert Air Basin (SEDAB).
- Imperial County portion of the SEDAB.

We applied data analysis methods using existing routine and special studies meteorological and air quality data. The methods were used:

- To document ozone exceedances in each of the downwind areas;

- To evaluate if ozone or ozone precursor transport between the upwind and downwind areas takes place;

- To evaluate when and how often ozone or ozone precursor transport between the upwind and downwind areas takes place;

- To estimate the general path of ozone and ozone precursor transport between the upwind and downwind areas; and

- To estimate the relative contribution of upwind and downwind emissions to ozone exceedances in the upwind area.

We used surface data and aloft wind data (when available) to prepare air-parcel trajectories for ozone violations at receptor monitoring sites. We accumulated precursor emissions along these trajectories and estimated the relative precursor contributions from the upwind and downwind air basins. At receptor locations, precursor contributions from the upwind air basins were typically between 20 and 80 percent on transport days; upwind contributions were higher than about 80 percent only at receptor locations at the boundary between air basins. The relative precursor contributions for nitrogen oxides and for reactive organic gases were always very similar.

The results indicate that the following issues are important for understanding pollutant transport: using aloft wind data, if available; allowing for reaction of precursors; using wind data from locations all along transport path, if available; and including biogenic emissions.

Precursor transport was significant on many days at Upper Sacramento Valley and North Central Coast monitoring sites; however, local contributions were dominant on other days. Local contributions were dominant on most days at Broader Sacramento Area and Imperial monitoring sites. It was extremely difficult to identify and document local days at Barstow in the Southeast Desert Air Basin.

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1. INTRODUCTION

1.1 PROJECT RATIONALE AND OBJECTIVES

The State of California has been divided into 14 air basins. Air pollution control districts or air quality management districts in each basin have been concerned with the control of local emissions and the impact of those emissions on pollutant concentrations in their basin. Although many of the basin boundaries were established with terrain features in mind, prevailing wind patterns in the state still transport pollutants from one basin to another. This effect has been clearly demonstrated on a number of occasions through the use of tracer releases.

The impact of pollutant transport on the ozone air quality in a downwind basin is a function of the precursor emissions in the upwind basin, the losses of pollutants by deposition and reaction along the transport path, the formation of ozone along the transport path, the meteorological situation which transports and mixes the pollutants, and the local precursor emissions in the downwind basin. Depending on the particular scenario, effective control strategies may require emission controls in the upwind air basin, the downwind air basin, or both.

The California Clean Air Act requires the California Air Resources Board (ARB) to assess the relative contribution of upwind pollutants to violations of the state ozone standard in the downwind areas. Past transport studies in California have documented pollutant transport on specific days, but have not always quantified the contribution of transported pollutants to ozone violations in the downwind area.

Grid modeling may ultimately be needed in many situations to evaluate the relative effects of different control strategies. However, many of the interbasin transport problems in the state involve complex flow patterns with strong terrain influences which are difficult and expensive to model. Limited upper air meteorological and air quality data in many areas generally restrict the evaluation, and thus the effective use, of grid models. In addition, interbasin transport between some of the air basins does not result in significant receptor impact and thus should not receive the detailed treatment afforded by grid modeling.

This project was designed to assess the contribution of transported pollutants to ozone violations within the air basins covered by this report using existing data and advanced data analysis techniques. This project provides an initial assessment of the pollutant transport contribution to ozone violations in these areas. The project results will improve future analysis, modeling, and control efforts.

The objectives of the project were:

- To determine the characteristics of ozone and ozone precursor transport within the air basins covered by this report; and

- To identify whether the contribution of transported pollutants to ozone violations in each downwind area was inconsequential, significant, or overwhelming, relative to locally-emitted pollutants.

The air basins covered for this project were:

- Transport between the San Francisco Bay Area Air Basin (SFBAAB), the Broader Sacramento Area, and the Upper Sacramento Valley.
- Transport from San Francisco Bay Area Air Basin to the North Central Coast Air Basin (NCCAB).
- Transport into the San Bernardino County portion of the Southeast Desert Air Basin (SEDAB).
- Transport into the Imperial County portion of the Southeast Desert Air Basin.

The three classes of transport contribution, as used by the ARB (1990) are listed below.

- Inconsequential contribution: Upwind emissions do not contribute significantly to exceedances of the state ozone standard in the downwind area. In this case, ozone violations are caused almost exclusively by local emissions, and thus only local efforts are required to reduce ozone concentrations in the downwind area.
- Significant contribution: Both local and upwind emissions contribute to ozone violations exceedances in the downwind area. In this case, efforts are required by both local and upwind areas to reduce ozone concentrations in the downwind area.
- Overwhelming contribution: Ozone exceedances are caused almost exclusively by upwind emissions, with very small or no contribution from local emissions. In this case, only efforts in the upwind area are required to reduce ozone concentrations in the downwind area.

The rest of this section summarizes the technical background for this project and presents our technical approach, a summary of the project results, and our recommendations for future use of the techniques applied during this project and for future work on pollutant transport.

1.2 TECHNICAL BACKGROUND

The impact of pollutant transport on the ozone air quality in a downwind basin is a function of the precursor emissions in the upwind basin, the losses of pollutants by deposition and reaction along the transport path, the formation of ozone along the transport path, the meteorological situation which transports and mixes the pollutants, and the local precursor emissions in the downwind basin.

Ozone is formed via a series of reactions involving sunlight, organic compounds, and nitrogen oxides. Three reactions illustrate the ozone cycle (Seinfeld, 1986). The formation of ozone begins with the photodissociation of nitrogen dioxide (NO_2) in the presence of sunlight:

$$NO_2 + \text{sunlight} \text{------>} NO + O \tag{1}$$

The atomic oxygen (O) quickly combines with molecular oxygen (O_2) to form ozone (O_3):

$$O + O_2 \text{------>} O_3 \tag{2}$$

Once formed, ozone reacts with NO to regenerate NO_2:

$$NO + O_3 \text{------>} NO_2 + O_2 \tag{3}$$

Most of the nitrogen oxides emitted into the atmosphere are emitted as NO; if ozone exists near where the NO is emitted, then the NO will reduce ozone concentrations by scavenging. However, reactive organic compounds contribute to the conversion of NO to NO_2 without consuming ozone; this increases the ozone concentration.

Additional issues which must be accounted for in the analyses for this project include the following:

- The transport of both ozone and ozone precursors must be considered. The major precursors are NO_x (including NO and NO_2) and reactive organic compounds (ROG, including hydrocarbons and carbonyls). However, the routine data for NO_x are of little value since concentrations are typically close to detection limits during much of the day, and there are little routine data for hydrocarbons or carbonyls. There are some routine non-methane hydrocarbons (NMHC) data, but these unspeciated data are often of little but qualitative use.

- Emissions of biogenic hydrocarbons are additional sources of hydrocarbons along a transport path; these emissions must be included in any emissions-related analyses.

- Three transport time-scales should be considered: same-day transport, overnight transport, and transported pollutants which remain overnight in the receptor area.

- Some areas have a very limited number of ozone violations (especially the North Central Coast and Imperial County). A larger data base was constructed by defining high ozone days to include days with an ozone concentration lower than the state standard; this improved the resulting analyses.

- Some areas have very limited air quality or meteorology data. Analyses for the areas with limited violations and aerometric data were performed on more of a case-study basis (versus a more statistically-based method which might be applied for the areas with more extensive data).

- All areas have little air quality and meteorology data aloft; this limited the comparisons of results from surface and aloft analyses to just a few cases.

1.3 TECHNICAL APPROACH

To meet the project objectives, modeling or data analysis methods could be applied. For this project, we applied data analysis methods using existing routine and special studies meteorological and air quality data. For this project, the methods were used:

- To document the number, location, magnitude, time of year, and time of day of ozone exceedances in each of the downwind areas;
- To evaluate if ozone or ozone precursor transport between the upwind and downwind areas takes place;
- To evaluate when and how often ozone or ozone precursor transport between the upwind and downwind areas takes place;
- To estimate the general path of ozone and ozone precursor transport between the upwind and downwind areas; and
- To estimate the relative contribution of upwind and downwind emissions to ozone exceedances in the upwind area.

For all monitoring sites in each of the air basins, we acquired the 1980-1989 hourly ozone air quality data on magnetic media from the ARB. We manipulated this data set and prepared the various tables and summaries in order to document the ozone exceedances in each downwind area. The results of this task helped focus the rest of the project on the important locations, time of day, and time of year.

Various data analysis methods can be applied to evaluate if, when, how, and how much ozone and ozone precursor transport has occurred. These methods can also be used to estimate the relative contribution of transported pollutants to ozone violations. The methods fall into three general categories: meteorological methods, air quality methods, and combined meteorological and air quality methods. We applied those data analysis methods which were best suited to the potential transport situation and which were supported by the available data.

A summary of the potential methods is provided below; additional details are provided where the major methods are applied in the results sections which follow. Many of these methods have been used before to investigate various aspects of ozone and ozone precursor transport (for example, ARB, 1990; Roberts, et al., 1990; Roberts and Main, 1989; Douglas, et al., 1990). By applying multiple methods to a specific ozone episode, one can build a strong case for a transport determination. This strength lies in the consensus conclusions drawn from applying multiple methods, not in the conclusions drawn from applying only one or two of the methods. Sometimes during our analyses, the results from applying different methods did not agree; in those cases we illustrated the differences and based our conclusions on the most reliable methods.

1.3.1 Meteorology Methods

Surface Air Flow Types: These are the air flow patterns used by the ARB meteorology section; they provide a snapshot of the air flow. Specific flow types are consistent with transport from one basin into another. For example, three of the Bay Area flow types would be consistent with transport into the NCCAB: northwesterly (Ia and Ib), northeasterly (IV), or bay inflow (VI). The frequency and persistence of these flow types during and immediately preceding ozone episodes at downwind monitoring sites would support transport. This also might be considered as a 'streamline' analysis, where the consistency of successive 4-hourly wind streamline maps are reviewed for transport potential (for example). An improved version using typical trajectories to classify flow types would better represent the integrated results of conditions that transport pollutants from a source to a receptor.

Surface Wind Run: Are surface wind speeds between major upwind source areas and the downwind receptor site consistent with the potential transport distance and with the time of the peak ozone concentration? The winds might be high enough to indicate a polluted air parcel could have traveled the distance between the source and receptor. In addition, the travel time (estimated from the surface wind speed) might match the time between the morning rush hour and the time of the ozone peak (if same-day transport). Both same-day and previous-day winds might need to be considered.

Aloft Wind Speed and Direction: As with the surface winds, are the direction and speed consistent with transport?

Air-Parcel Trajectories: Air-parcel trajectories estimate the path of an hypothetical air parcel over a selected time period. Back trajectories follow an air parcel to illustrate where the air might have come from; forward trajectories follow an air parcel on the way from a source region to illustrate where an air parcel might go. Do forward and back trajectories support transport?

Surface Pressure Gradients: Are pressure gradients between air basins consistent with transport between them? And with the air flow types and with trajectory results? Note that synoptic gradients can be misleading in areas with strong land-sea diurnal flow patterns, such as the northern California coast.

Depth of Surface Layer: Was the surface layer shallow enough to keep pollutants poorly dispersed, but deep enough to allow penetration of the pollutants up valleys or over passes?

Surface Temperatures: Are the maximum temperatures in the upwind and downwind air basins (and in between) the same, possibly indicating a similar air mass, or different? Does the diurnal temperature pattern at the downwind site indicate a drop in temperature due to the arrival of a sea breeze? How is the diurnal temperature profile related to the ozone profile? Note that it may be possible for air parcels to arrive at downwind site via different routes and with different temperatures and humidity histories (into the northern San Joaquin Valley (SJV) from the Bay Area via hot Livermore or via the cooler Sacramento River delta, or from the Bay Area to Hollister via hot Santa Clara Valley or via cool Monterey Bay, for example). Note that this method is especially weak by itself, but could lend support to conclusions from other methods.

The Presence or Absence of a Convergence Zone, or Other Critical Flow Characteristic: In the case of potential transport from the Santa Clara Valley to Hollister, it seems like the absence of the convergence zone near Gilroy is a necessity, otherwise pollutants are likely transported aloft and then by the westerlies or northwesterlies into the SJV. The presence or absence of the convergence zone could be identified by winds at monitoring sites just north and south of the suspected area.

1.3.2 Air Quality Methods

Geographical Extent of High Ozone Concentrations: If high ozone concentrations extend throughout the upwind and downwind air basins, it might be assumed that the same general air mass exists in both basins. However, this is a very weak argument, unless the conclusions from other methods, such as wind flow patterns and the timing of the ozone peaks along the potential transport path, also support such a conclusion.

Timing of Peak Ozone Concentrations Along a Potential Transport Path: Analyses of the time of peak ozone concentration at various monitoring sites can yield useful information on transport patterns and source areas. In most major source areas of interest in California, transport winds are light in the morning, allowing ozone precursor concentrations to build up and ozone to form. By noon, transport winds generally increase and the ozone moves downwind out of the major source regions. This leads to peak ozone concentrations in the principal source areas around 1100-1300 PST with a decrease thereafter as the ozone-rich air is replaced by cleaner air from upwind. Peak ozone times after 1300 PST generally signify transport into the area from an upwind source region.

If a number of ozone monitoring sites lie along a suspected transport path, then the magnitude and timing of peak ozone concentrations can be evaluated. A consistent transport pattern exists if the ozone peaks occur later at each successive downwind site, and if the time between peak concentrations is consistent with the measured wind speeds (for example, see discussion in section 4.3 of Roberts, et al., 1990). Often, a consistent pattern does occur, but the pattern finally breaks down when an ozone peak is much earlier than the peak at the site just upwind; this situation occurs regularly at Turlock in the San Joaquin Valley.

Note that this technique works best when there are few emissions sources along the transport path; otherwise allowances must be made for modifications to the diurnal ozone profiles by local emissions (especially for the reaction of fresh NO with ozone). In addition, this technique only works when the transport occurs at the surface, rather than aloft. There is little routine information available to directly demonstrate that aloft transport does occur.

<u>Geographical Extent of Exceedances and Similarity of Ozone Peak Concentrations:</u> These two methods are sometimes used to suggest that the upwind and downwind monitoring sites were part of the same air mass. However, these are very weak arguments except for the most remote monitoring sites with no local or regional emissions nearby (some Sierra parks, for example). When used in combination with other methods (regular flow patterns and successive timing of ozone peaks along the transport path, for example), these methods provide some support to a conclusion of transport. But two specific conditions weaken any conclusions drawn from these methods when there are any local emissions:

- There is a strong synoptic contribution to ozone episodes in all of California, resulting in ozone episodes due to local emissions in areas obviously not connected by transport; the South Coast Air Basin (SoCAB) and Sacramento, for example.

- A similar diurnal ozone concentration pattern occurs daily at nearly all monitoring sites in the state (driven by the diurnal solar cycle); sometimes the peak concentration is as low as 5 or 6 pphm, often the peak is 8 or 9 pphm (almost reaching the state standard), and on other days the peak exceeds the state standard. This alone does not demonstrate that pollutant transport has occurred.

1.3.3 Combined Meteorological and Air Quality Methods

<u>Relative Emissions in the Upwind and Downwind Areas:</u> There are a number of methods to estimate the relative emissions contributions to downwind ozone exceedances, from simple to more complex. As the method gets more complex, the strength of the transport conclusion increases. Ways to estimate the relative emissions contributions include:

- A simple ratio of precursor emissions in the upwind air basin to those in the downwind air basin;

- A simple ratio of precursor emissions in a portion of the upwind air basin (that portion most connected by geography and wind patterns to the downwind area) to those in the downwind area;

- A ratio of upwind to downwind emissions, with emissions accumulated along a typical trajectory path upwind and downwind of a division between the air basins; and

- A ratio of upwind to downwind emissions, using meteorological and photochemical models.

1.4 RESULTS

The following is a summary of the results of our analyses. Listed first are general results on ozone violations, transport-path analyses, and precursor contribution estimates. These results include comments on how well the data analysis methods performed and the major assumptions and limitations of the methods. Results specific for each receptor area are presented next.

Ozone Violations:

- Violations of the state and federal ozone standards occur at receptor monitoring sites in the Upper Sacramento Valley, the Broader Sacramento Area, the North Central Coast Air Basin, and the San Bernardino and Imperial County portions of the Southeast Desert Air Basin. Violations are more frequent at monitoring sites near upwind urban areas such as the South Coast Air Basin, the Broader Sacramento Area, and the San Francisco Bay Area Air Basin. Ozone violations at North Central Coast and Imperial monitoring sites were infrequent; this made some analyses difficult.

- Ozone violations at downwind receptor sites generally occurred during the months of June through October, essentially the same months as the upwind areas.

- Ozone violations produced by pollutant transport generally occur later in the day than ozone violations produced by local pollutants. The timing of the peak ozone concentration at a given monitoring site is a function of the distance from the upwind area, the speed of the winds which transport the pollutants, and the rate of formation of ozone. Locally-produced violations at the downwind receptor sites usually occurred between 1100 and 1300 PST; carryover could also result in early ozone violations. Transport-produced violations usually occurred between 1300 and 1800 PST. However, there were some cases of late-night transport which resulted in 1100-1300 PST ozone violations at the Redding monitoring site; this may occur more often at Redding and at other sites, but sufficient data was not available to confirm it. Ozone violations at the downwind sites within a large urban area (Folsom and Auburn in the Broader Sacramento Area, for example) occurred in the afternoon but were produced mostly by local precursors.

- Multiple ozone peaks at a number of monitoring sites, including Chico, Redding, and Pinnacles, indicate multiple transport paths. The first peak was usually produced from local precursors, but sometimes from carryover of pollutants from the previous day or from transported pollutants which arrived late at night. The second peak was usually from transported pollutants.

Transport-path Analysis Results:

- Generating large numbers of air parcel trajectories was a good method to identify the consensus transport paths for each receptor.

- Air parcel trajectories generated from surface wind measurements were consistent with expected transport paths based on results from past field, analysis, and modeling studies.

- Wind measurements are required to properly represent transport in the areas where convergence zones occur, such as in the Upper Sacramento Valley south of Redding and in the Santa Clara Valley between Morgan Hill and Gilroy. These measurements are required at sites on both sides of the convergence zone, both near the convergence zone and upwind 10-30 kilometers.

- Aloft transport to Redding seemed to occur on a number of days, even though a convergence zone was often present at the surface between Redding and the Broader Sacramento Area. For example, on August 7, 1990, aloft trajectories indicate transport from the south, but surface trajectories show transport from the northwest most of the day.

- Transport paths using upper air wind measurements were often consistent with those generated from surface winds, but they were also sometimes different, especially at the 800 meter level.

- When transport paths using upper air winds were consistent with those using surface winds, the transport aloft was much faster than the transport at the surface. Fast transport aloft increased the precursor contribution of the upwind area, relative to the downwind area. However, this increase was small if same-day transport or transport over short distances was involved. The largest differences between precursor contribution estimates using surface data and those using aloft data occurred when there was overnight transport.

- For most receptor sites, we identified one major transport path. However, for Hollister, Pinnacles, and Barstow, we identified two potential transport paths. For Hollister and Pinnacles, transported pollutants could arrive via either the Santa Clara Valley or Monterey Bay; for Barstow via either Soledad Canyon or Cajon Pass.

Precursor Contribution Estimate Results:

- The precursor contributions of upwind and downwind areas were estimated for two ozone precursors: reactive organic gases (ROG) and nitrogen oxides (NO_x). However, the relative contribution estimates of the upwind and downwind areas using ROG were very close to those using NO_x.

- Precursor contribution estimates were made for cases with and without the loss of precursors via reaction. Including losses via reaction increased the precursor contributions from the local area and decreased the contributions from the upwind area. Using daytime and nighttime first-order reaction rates for both ROG and NO_x was simple to do and was more realistic than not using any reaction rates. Thus, results are reported for cases with reaction included.

- When pollutant transport to a receptor site occurred, at least 10-20 percent of the precursor contributions usually came from the local air basin.

- However, an exception occurred when there was transport from the upwind air basin to a monitoring site just across the boundary into the downwind air basin; this resulted in 95-100 percent precursor contribution from the upwind air basin. In this project, this exception occurred when there was transport from the San Francisco Bay Area Air Basin to the Hollister monitoring site in the North Central Coast Air Basin.

- We used an emissions inventory which included an estimate of biogenic emissions. Because current biogenic emissions estimates are significant in the Upper Sacramento Valley and because the receptor sites are well away from the upwind boundary, there was at least 30-40 percent precursor contributions from the local air basin. Thus, there were no cases of overwhelming transport to Upper Sacramento Valley monitoring sites.

- Precursor contribution estimates using aloft trajectories resulted in larger contributions from the upwind area than did estimates using surface trajectories. This is because the aloft trajectories result in faster transport with less time for precursors to be lost via reaction.

Summary of the local and transport classifications for each receptor area:

- Upper Sacramento Valley: For Chico, Red Bluff, and Redding, we identified ozone violation days with both local and transport contributions. However, none of the transport days studied were overwhelming. The ARB (1990) did identify an overwhelming transport day to Arbuckle and Willows, October 7, 1987; however the overwhelming day was not included in the transport days that STI studied.

- Broader Sacramento Area: For sites at the upwind edge of the Sacramento urban area, Sacramento Metro Airport and 13 and T, we identified ozone violation days with both local and transport contributions. However, for sites within and downwind of the Sacramento urban area, local contributions were dominant.

- North Central Coast Air Basin: For Hollister and Pinnacles, we identified ozone violation days with both local and transport contributions. However, the Pinnacles local days might be reclassified as transport if aloft data were available to use in our analyses. On the only day when high ozone concentrations were measured at Carmel Valley in 1990 but did not exceed the state standard, and sufficient data was available, we identified only local contributions. However, infrequent ozone exceedances and insufficient meteorological data prior to 1990 limited our analyses.

- San Bernardino County portion of the Southeast Desert Air Basin: For Victorville and Lancaster, we classified all ozone violation days as transport from the South Coast Air Basin. For Barstow, most ozone violation days were the result of transport from the South Coast Air Basin; however, we identified a few ozone violation days which might be the result of local contributions. For Trona, most ozone violation days were the result of transport from the San Joaquin Valley; however, we identified a few ozone violation days which might be the result of local contributions. For Twentynine Palms, all of the ozone violation days were the result of either same-day transport from the South Coast Air Basin or carryover of pollutants transported on the previous day. On many days in the Southeast Desert, it was very difficult to separate the effects of local contributions from those resulting from pollutant carryover or continued ozone formation in the downwind area.

- Imperial County portion of the Southeast Desert Air Basin: For Imperial, ozone violation days were the result of mainly local contributions; with little evidence of transport contributions.

1.5 RECOMMENDATIONS

The following are recommendations for future work, separated into data analysis and field measurement recommendations.

Data Analysis:

- Consider using an emissions-accumulation box which is narrower than 45 kilometers at distances within about 50 kilometers of the receptor area. This would reflect the narrower area of potential influence close to a receptor.

- Perform additional data analyses of the August 7-8, 1990 ozone episode in the Sacramento Valley. Data from the SACOG field study should help.

- Prepare additional precursor contribution estimates using an emissions inventory with fewer biogenics and with no biogenics. With the current biogenics inventory, the Upper Sacramento Valley contributions remained high even when obvious transport occurred.

- Prepare additional aloft trajectories and precursor contribution estimates for the Broader Sacramento Area receptor sites, using SACOG data.

- Ozone exceedances at Redding often occur when there is a convergence zone in the Upper Sacramento Valley and when there is the potential for nighttime transport aloft. A complete understanding of how these exceedances occur will require aloft meteorological measurements north of the convergence zone, preferably near Redding.

- Prepare aloft trajectories and precursor contribution estimates for 1990 NCCAB exceedances using aloft meteorological data for Hollister and Moss Landing, once it is available from the SJVAQS/AUSPEX. This is especially important for understanding potential aloft transport to Pinnacles. Many of the surface back trajectories for Pinnacles arrive from the west via Monterey Bay, while the aloft trajectories may arrive from the north.

- Prepare surface and aloft back trajectories and precursor contribution estimates for 1991 NCC exceedances, once the data are available. Aloft data will be available from the radar profilers operated at Moss Landing, Hollister, and Bear Valley (near Pinnacles); this should be an excellent data set for understanding Hollister and Pinnacles exceedances.

- Re-evaluate the need for good data in the Moss Landing and Morgan Hill/Gilroy areas when preparing trajectories for Carmel Valley exceedances. If back trajectories for Carmel Valley arrive from the north and west, then good data in these other locations may not be required. CIMIS data for Castroville may be sufficient in the Moss Landing area and the Santa Clara convergence zone may not matter for Carmel Valley exceedances.

- Use aircraft and upper air meteorology data from the SJV/AUSPEX field study to evaluate transport from the San Francisco Bay Area to the North Central Coast.

- Prepare relative ozone and nitrogen oxides flux estimates using data from additional monitoring sites along potential transport paths.

- Prepare forward trajectories from multiple source areas within the San Francisco Bay Area Air Basin for typical days; use the transport patterns to classify ozone violation days.

Field Measurements:

- Ozone monitoring along potential transport paths is often critical to understanding the when and by what route transport takes place. Monitoring should be performed at a few sites between the Broader Sacramento Area and Upper Sacramento Valley receptor sites at Redding and Chico, especially on the west side of the Sacramento Valley; Red Bluff and either Arbuckle or Colusa would be a major addition.

- Recently expanded meteorological measurements at the SFBAAB/NCC boundary should be continued. Measurements at San Martin, Gilroy, Hollister, Davenport, Salinas, King City, and Aromas are especially critical. High data quality from the PG&E site at Moss Landing is also critical to understanding NCC ozone exceedances.

- Acceptable operation of the buoys offshore from Point Reyes to southern Monterey County should continue; invalid data or periods of non-operation have occurred in the past and jeopardize the documentation of offshore transport to the NCC. These six buoys are currently operated by four different agencies (U.S. Coast Guard, the Minerals Management Service, the National Weather Service, and the U.S. Army Corps of Engineers). Although long-term oversight of the operation may be passing to the National Buoy Center, budget will continue to be a problem.

- In this study, upper air meteorological data was critical for determining transport paths and estimating precursor contributions. This aloft data was obtained during special short-term field studies, but the data was not always available on ozone violation days or at the appropriate locations. Continuing ARB programs such as the transport corridors project to obtain aloft meteorological and air quality data are critical for determining transport paths and estimating precursor contributions in the future.

1.6 REPORT CONTENTS

The remaining sections of this report document the ozone violations in the downwind areas and present data analysis results for pollutant transport to each of the areas. Each section includes results for the analysis methods applied for that area and additional details on how the methods were applied. Additional tables of data summaries are included in the appendices.

2. TRANSPORT TO THE UPPER SACRAMENTO VALLEY

This section presents the analysis results for the Upper Sacramento Valley as the receptor area, including the documentation of the ozone violations in the area and analyses of air-parcel trajectories and precursor contributions. At the beginning of each subsection, we have provided a summary discussion of the methods that were used to perform the analyses. These discussions apply to the analyses performed for all receptor areas and will not be repeated in subsequent analyses sections.

The Upper Sacramento Valley area is defined as the counties of Shasta, Tehama, Glenn, Butte, and Colusa. The upwind areas which might contribute transported pollutants to the Upper Sacramento Valley area are the San Francisco Bay Area Air Basin (SFBAAB) and the Broader Sacramento area. Figure 2-1 is a map of the general area which shows these three areas. Note that if pollutants are transported from the SFBAAB to the Upper Sacramento Valley, they must first pass through the Broader Sacramento area. The natural geographic division between the Broader Sacramento area and the Upper Sacramento Valley is on an east/west line at Sutter Buttes.

2.1 OZONE VIOLATIONS

This subsection is divided into two parts. The first summarizes the general methods used to document the number, location, magnitude, time of year, and time of day of high ozone concentrations in each of the downwind areas. The second part presents a general description of the ozone air quality in the Upper Sacramento Valley. The purpose of this analysis is to provide an objective understanding of ozone air quality at the receptor sites in that area; thus providing a basis for the more-detailed interpretative analyses in the following sections. The results in this section include basic statistics on where, when, and how often high ozone concentrations occur in the area and discussions of diurnal patterns of ozone concentrations.

2.1.1 Methods Used to Document Ozone Violations

We have focused our attention on the last ten years of monitoring data (1980-1989). Emissions changes have occurred during that time; however, there have been so few ozone monitoring sites in the area, and violations of the state ozone standard occur so infrequently, that using a shorter period would result in less-reliable statistics. These years are representative of recent experience after extensive controls had been implemented in the late 1970's.

For all monitoring sites in each of the four selected areas, we acquired the 1980-1989 hourly ozone air quality data on magnetic media from the ARB. We manipulated this data set and prepared various tables and summaries, including the following:

- A list of all days when the state ozone standard was exceeded, by monitoring site. The list includes the site, data, maximum ozone concentration on that day and the hour of occurrence, the number of hours with the maximum concentration, and the hourly ozone

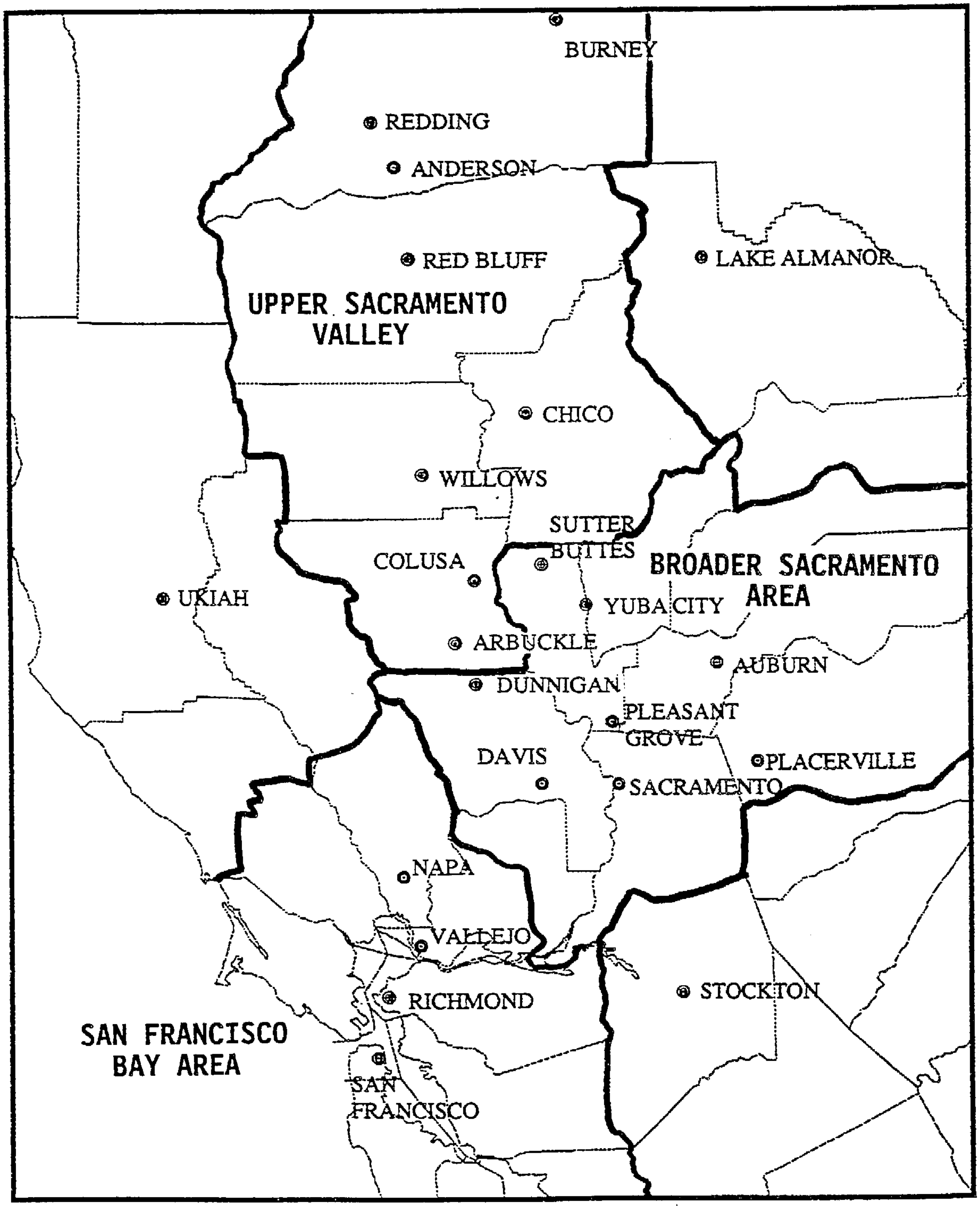


Figure 2-1. Map of Northern California Showing the Upper Sacramento Valley, the Broader Sacramento Area, and the San Francisco Bay Area.

concentrations for that day. For an example, see tables in Appendix A. Note that some monitoring sites operated for only a few years during the 1980-1989 period. For some monitoring sites, there were very few days exceeding the state ozone standard; thus we prepared this list using a lower ozone concentration (greater than or equal to 8 pphm) in order to obtain a larger data set and thus to improve the resulting analyses. We used these lists as a basis for other analyses and as a general reference on exceedance characteristics.

- A table of the number of days with maximum ozone concentrations exceeding either the state ozone standard or the lower cutoff concentration, by monitoring site. We used this list to select the locations where exceedances occurred most frequently for use in subsequent analyses. For an example, see Tables 2-1, 4-1, 5-1, or 6-1.

- Plots of the hourly mean, minimum, and maximum ozone concentrations and of the frequency of the first hour of the ozone concentration maximum, by monitoring site. We used these charts to understand the timing of high ozone concentrations and how this timing might be similar or different at monitoring sites along potential transport paths. For an example, see Figures 2-5, 2-8, 4-5, 4-8, 5-2, or 6-3.

- Time-series plots of ozone concentrations during and immediately preceding ozone episodes. We also used these plots to better understand the diurnal ozone concentration profile and how the profile might be similar or different at monitoring sites along potential transport paths. In addition, similarities in shape, duration, and existence of multiple peaks at multiple sites in the receptor area might indicate that both sites are influenced by the same source area (could be either local or transport from upwind). Similarities in shape, duration, and existence of multiple peaks along a potential transport path might indicate that transport had occurred.

- Tables of ozone peak concentrations on specific days in the upwind and downwind areas. We used these tables to visualize the coincident frequency and timing of ozone episodes in the potential source and receptor areas of a transport couple.

2.1.2 Ozone Violations in the Upper Sacramento Valley

Long-term ozone records are available from only two sites in the Upper Sacramento Valley, Chico and Redding. Ozone monitoring has been performed at Yuba City since 1982; this site is on the upwind border between the Upper Sacramento Valley and the Broader Sacramento area. A number of other monitoring sites in the area have been operated for periods of at least two years during 1980-1989.

Table 2-1. Ozone Exceedances at Upper Sacramento Valley and Nearby Monitoring Sites

Number of Days with Maximum Ozone > 9 pphm				
Site Name	Site Number	Years of Operation*	Total	Average Per Year
Redding	45560	1980-1984	58	12
Redding	45564	1985-1989	43	9
Anderson	45558	1987-1988	15	8
Chico	04628	1980-1989	28	3
Willows	11673	1980-1987	30	4
Colusa	06643	1980-1987	39	5
Arbuckle	06645	1984-1987	43	11
Dunnigan	57574	1982-1984	21	7
Yuba City	51895	1982-1989	113	14
Pleasant Grove	51897	1982-1989	89	11

* Note that monitoring did not always start in January. Ozone data for July through September available if listed, at a minimum.

Table 2-1 shows summary statistics for ozone concentrations exceeding the state standard at Upper Sacramento Valley and nearby monitoring locations for the years 1980-1989. The table includes the total number of days exceeding the state standard and the average number of days per year. The table also lists the years of operation for each site. Note that monitoring did not always start at the beginning of a year, so there are a few partial years included in the data. The federal ozone standard was only exceeded two times during this period, both at Redding in 1987. Figures 2-2 and 2-3 show the monthly frequency of the state ozone exceedances at the Upper Sacramento Valley monitoring sites. Figure 2-4 shows similar data for two ozone monitoring sites in the Broader Sacramento area, but near the Upper Sacramento Valley border.

The table and figures give a useful summary of ozone conditions from north to south in the Upper Sacramento Valley area. As indicated in the table, the yearly frequency of ozone exceedances is highest at Redding and at Anderson, with frequencies almost as high as at the Broader Sacramento sites of Yuba City and Pleasant Grove. Ignoring Redding and Anderson, the frequency of exceedances decreases from south to north; Dunnigan is a minor exception, but the site is immediately next to Interstate Highway I-5 and probably influenced by fresh NO emissions. This general decrease in ozone exceedance frequency is consistent with pollutant transport; local emissions and carryover are likely to contribute more at Anderson and Redding than at the other Upper Sacramento Valley sites.

The figures show that all of the ozone exceedances in the Upper Sacramento Valley occurred during the months of April through October, with

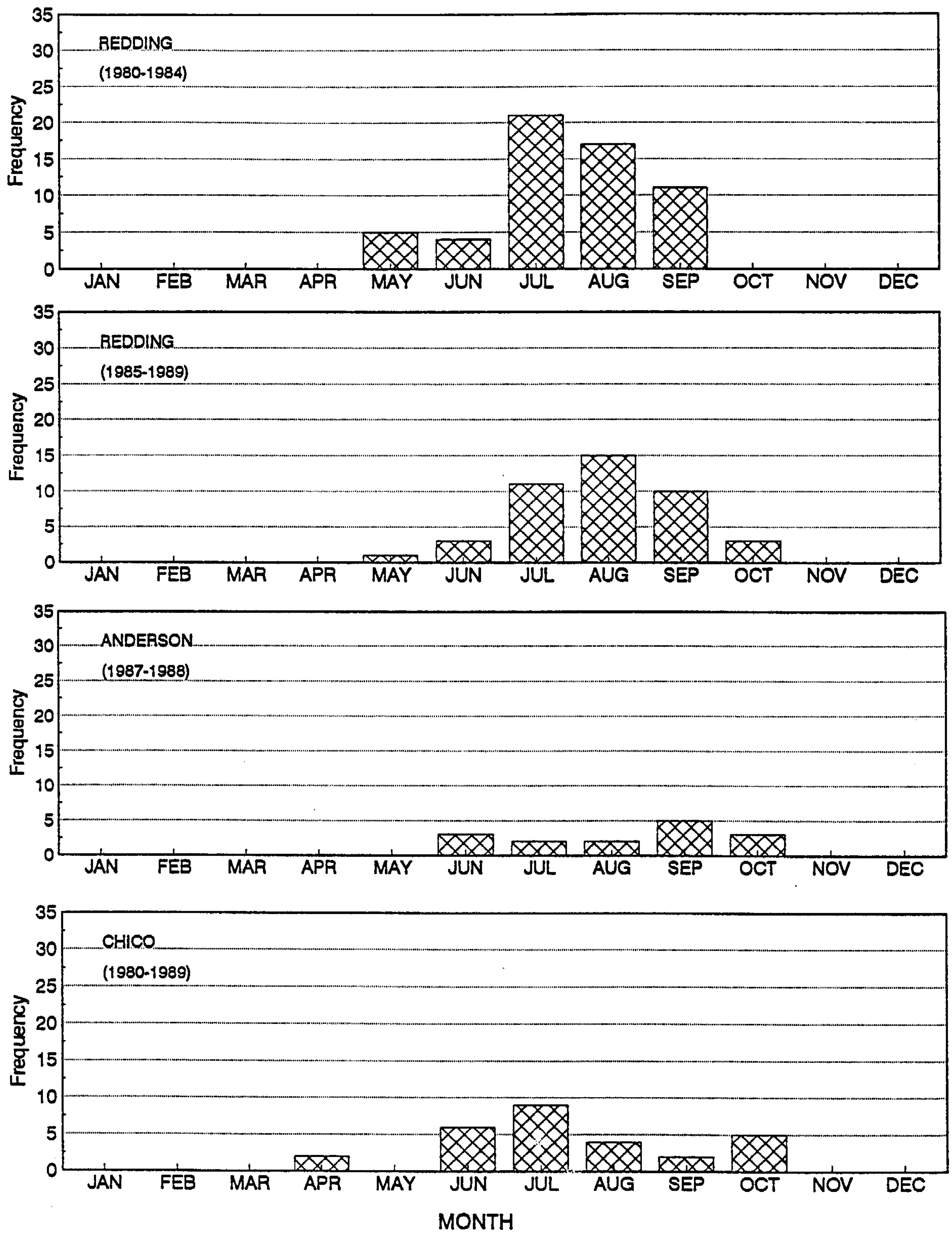


Figure 2-2. Monthly Frequency of State Ozone Exceedances (O_3 >9 pphm) at Redding, Anderson, and Chico.

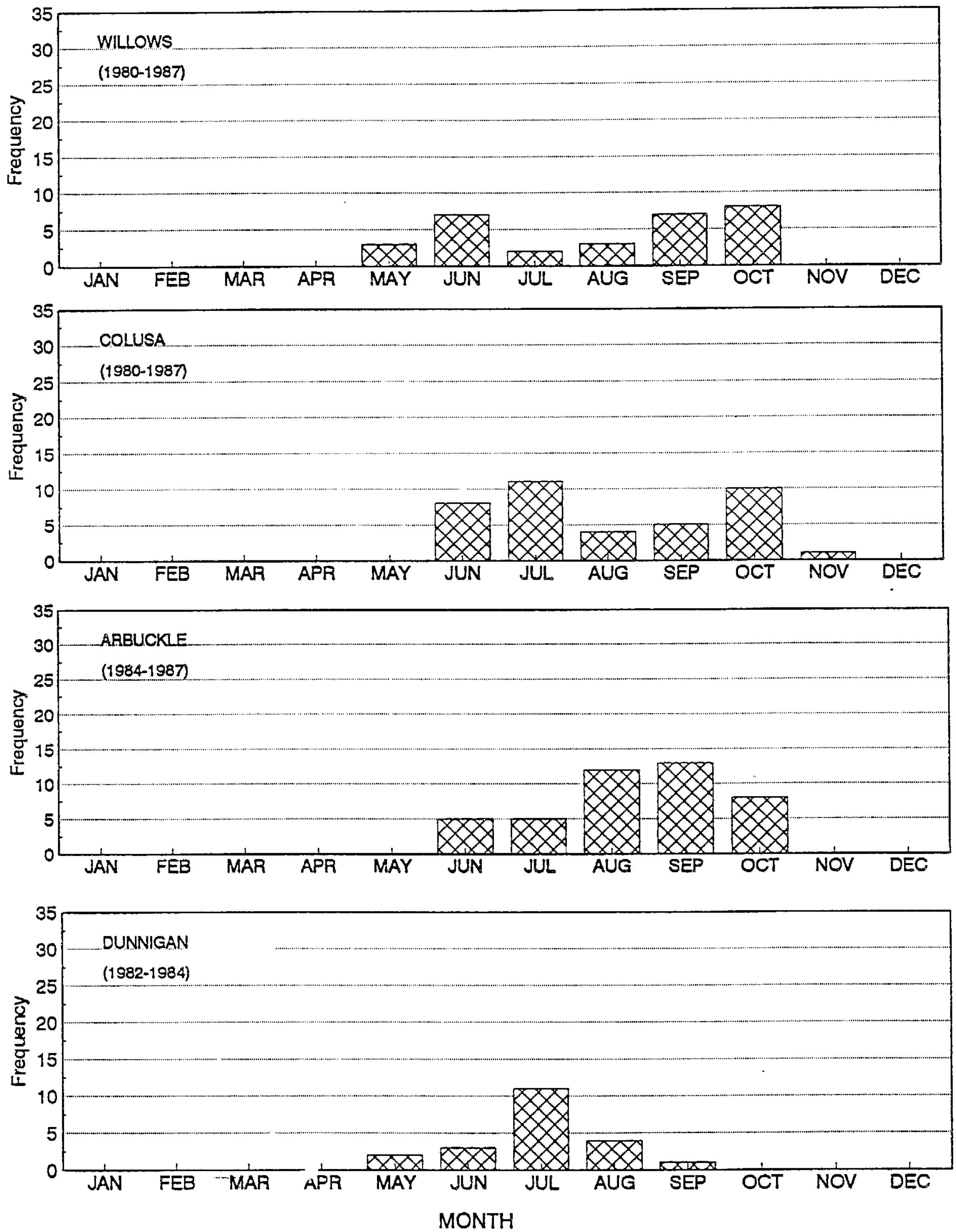


Figure 2-3. Monthly Frequency of State Ozone Exceedances (O_3 >9 pphm) at Willows, Colusa, Arbuckle, and Dunnigan.

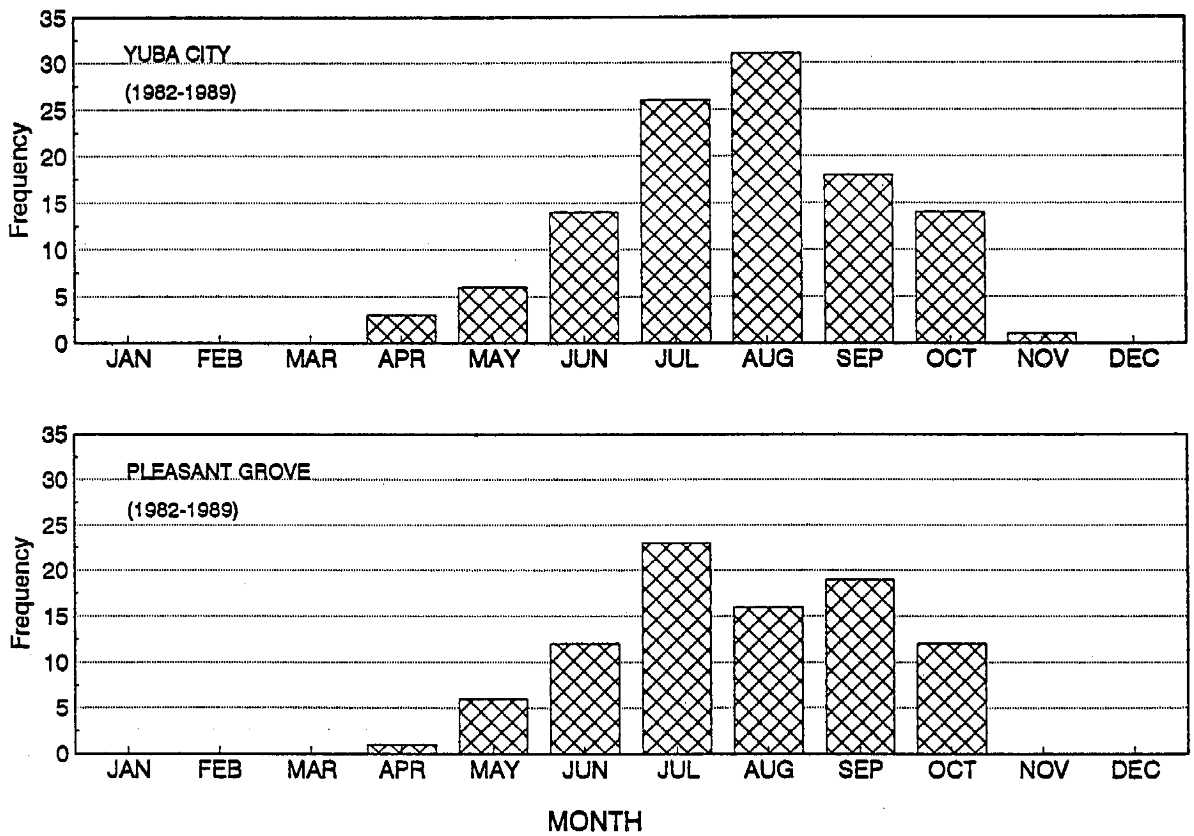


Figure 2-4. Monthly Frequency of State Ozone Exceedances (O_3 >9 pphm) at Yuba City and Pleasant Grove.

relatively few in April and May. Exceedances at Redding occurred mostly during July, August, and September; whereas at Chico almost as many exceedances occurred during October as during the summer months. Closer to the upwind border at Willows, Colusa, and Arbuckle, the exceedances are more evenly distributed from June through October. Exceedances at the Yuba City site were most frequent in August, but most occurred from June through October.

Figures 2-5, 2-6, and 2-7 give the hourly mean, minimum, and maximum ozone concentration for ozone exceedance days at the Upper Sacramento Valley monitoring locations. The relative timing of the diurnal ozone peak varies by location and is summarized below:

Location	Time (PST) of Peak Ozone Concentration
Redding	1100-1400
Anderson	1200-1400
Chico	1400-1700
Willows	1400-1600
Colusa	1400-1600
Arbuckle	1400-1600
Dunnigan	1400-1600
Yuba City	1400-1600
Pleasant Grove	1300-1500

The time of the peak concentration is an indicator of source-receptor relationships. The early peak times at Redding and Anderson suggest the effects of local sources and possibly carryover, while the later peaks at all of the other locations indicate transport effects. The intermediate sites of Willows, Colusa, Arbuckle, Dunnigan, and Yuba City, which only cover an up-valley distance of about 70 km, have about the same mean time of peak concentration.

The shape and magnitude of the mean curves are similar for the intermediate sites. However, the mean curves for Redding and Anderson rise much faster in the morning, indicating precursors from nearby sources or from carryover. Notice that the mean curve and the minimum and maximum points for Redding and Anderson are relatively constant from about 1100 to 1600 PST, indicating that ozone concentrations are typically remaining high in the area for a few hours. Also notice that the Redding mean curve begins decreasing quickly after about 1600 PST, whereas the Anderson and Chico mean curves decrease at a slower rate. This slower rate of decrease may indicate that late arriving transport or late afternoon stagnation is a significant factor.

A review of individual diurnal ozone conce trations at Redding and Anderson on exceedance days identified that there were often two peaks, one at about 1100-1200 PST and a second at about 1400-1700 PST. For example, of the 20 ozone exceedances days at Redding during 1987, there were two ozone peaks on one-half of the days. The second peak never had a concentration higher than the first peak. If the first peak is caused by local emissions and possibly carryover, then the second peak could be caused by a number of things, including:

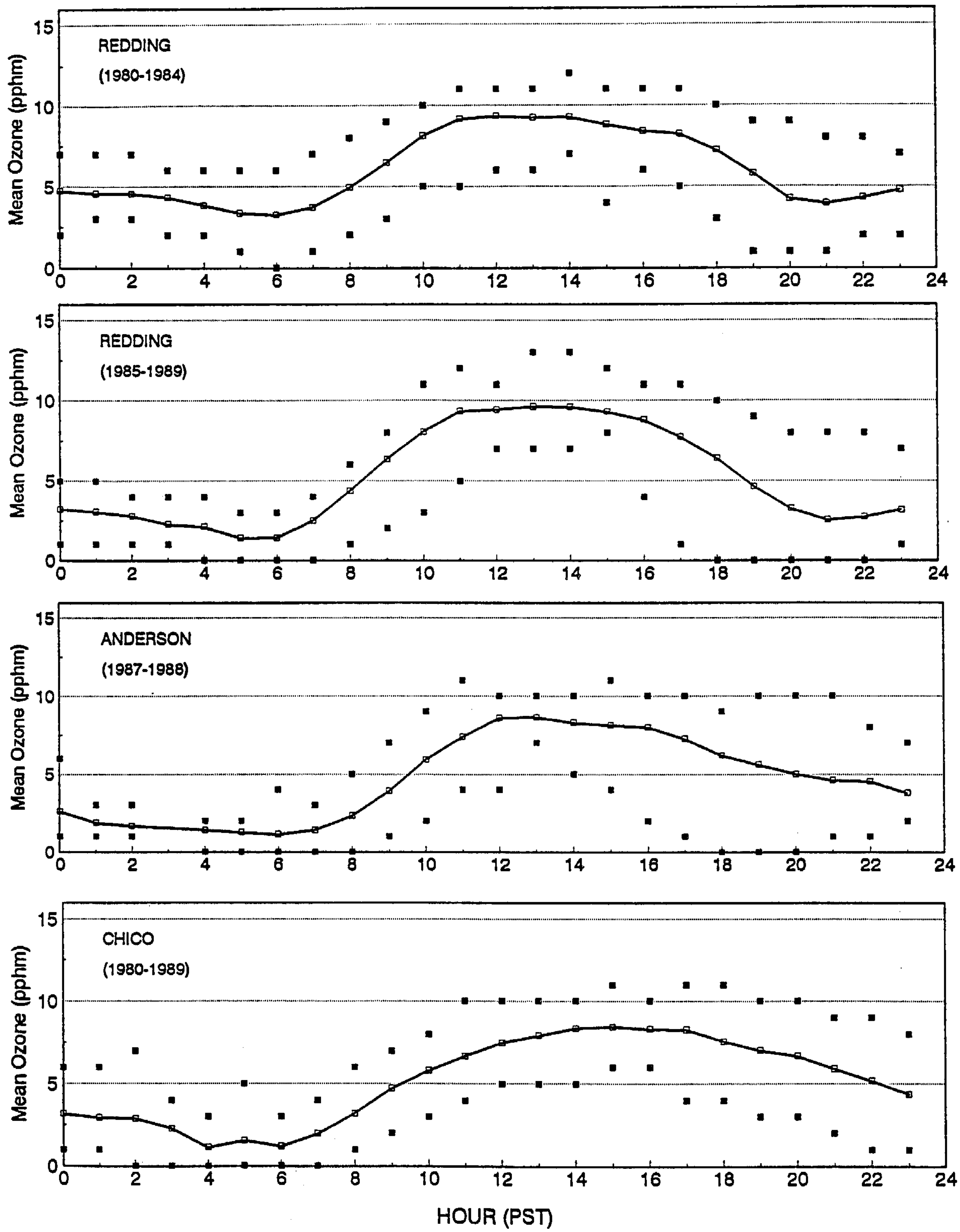


Figure 2-5. Hourly Mean, Minimum, and Maximum Ozone Concentrations for Ozone Exceedance Days at Redding, Anderson, and Chico.

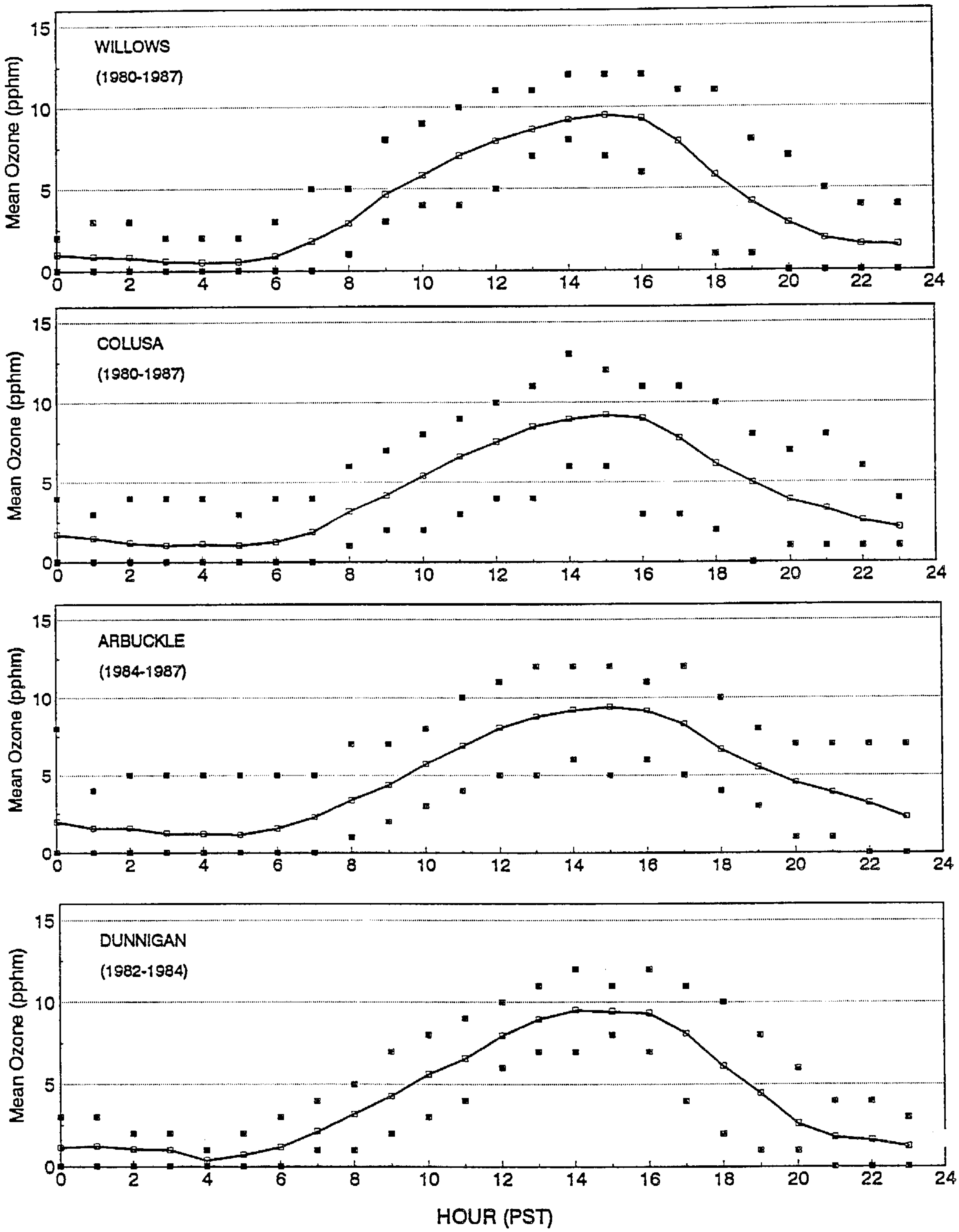


Figure 2-6. Hourly Mean, Minimum, and Maximum Ozone Concentrations for Ozone Exceedance Days at Willows, Colusa, Arbuckle, and Dunnigan.

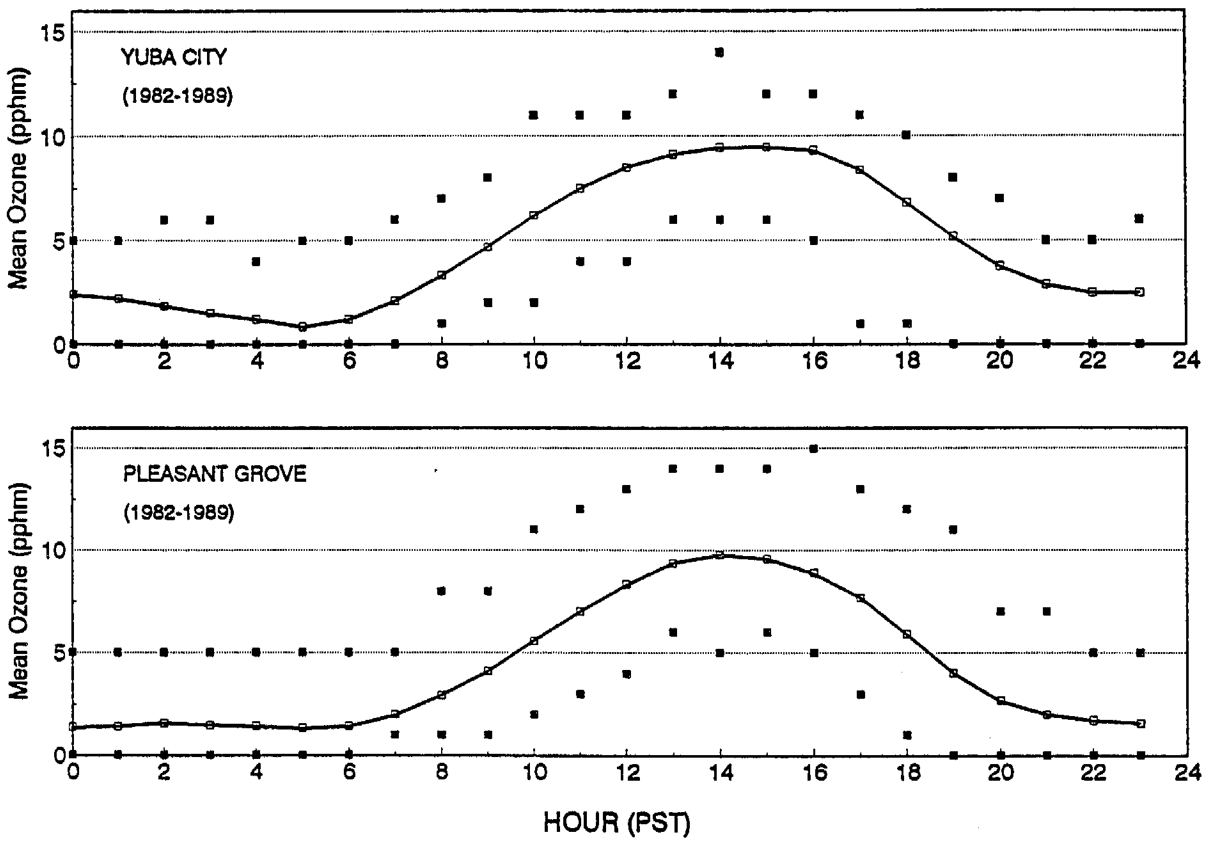


Figure 2-7. Hourly Mean, Minimum, and Maximum Ozone Concentrations for Ozone Exceedance Days at Yuba City and Pleasant Grove.

- A late-arriving transport peak;
- Light, fluctuating winds during the morning emissions period;
- Light, fluctuating winds during the peak ozone period; and
- Non-uniform fresh emissions near the monitoring site which might "titrate" some of the ozone.

If late-arriving transport is causing the second peak, then trajectory analysis should be able to show transport (see Sections 2.2.2 and 2.4.2).

The Redding mean curve increases slightly beginning about 2200 PST while the Chico curve has a longer tail with slowly decreasing concentrations until about 0400 PST the next morning. Surprisingly, overnight concentrations at Redding are 4-5 pphm, while the intermediate sites have concentrations of less than 2 pphm. Either the Redding monitoring site is influenced by clean background air at night or it is not influenced by fresh auto emissions as most urban sites are at night. The intermediate sites must be influenced by fresh emissions on a regular basis.

Another way to evaluate the timing of peak ozone concentrations is to prepare frequency plots of the first hour of the maximum concentration (see Figures 2-8, 2-9, and 2-10). At Redding, the ozone peak typically occurs first between 1000 and 1400 PST, but most often at either 1100 or 1200 PST. This is too early for same-day transport and indicates either local contributions or carryover or overnight transport contributions, possibly from fumigation from layers aloft. The ozone peak occurs two-to-four hours later at Chico and the intermediate sites of Willows, Colusa, Arbuckle, and Dunnigan. Notice some peaks occur as early as 1300 PST at Arbuckle, the most southern site, and there is some evidence of later peaks along a south-to-north path from Arbuckle to Colusa to Willows. Maximum concentrations at Yuba City and Pleasant Grove occur between 1300 and 1500 PST, a little earlier than the intermediate sites in the Upper Sacramento Valley, but later than at Redding.

2.2 TRANSPORT-PATH ANALYSES

This subsection is divided into two parts. The first summarizes the general methods that were used to identify transport paths and to evaluate pollutant transport to Upper Sacramento Valley monitoring sites. We also used these methods for other receptor areas. The second part summarizes the results of our trajectory analyses and discusses those results. The purpose of these analyses is to evaluate if transport takes place, how often it occurs, and to estimate the general path of pollutant transport to the Upper Sacramento Valley.

2.2.1 Summary of Trajectory Methods

During our determination of potential transport paths, we usually performed the following tasks in succession:

- Performed an analysis and review of past field, data analysis, and modeling studies in the area of interest. We used this review to identify potential transport paths to the downwind air basin.

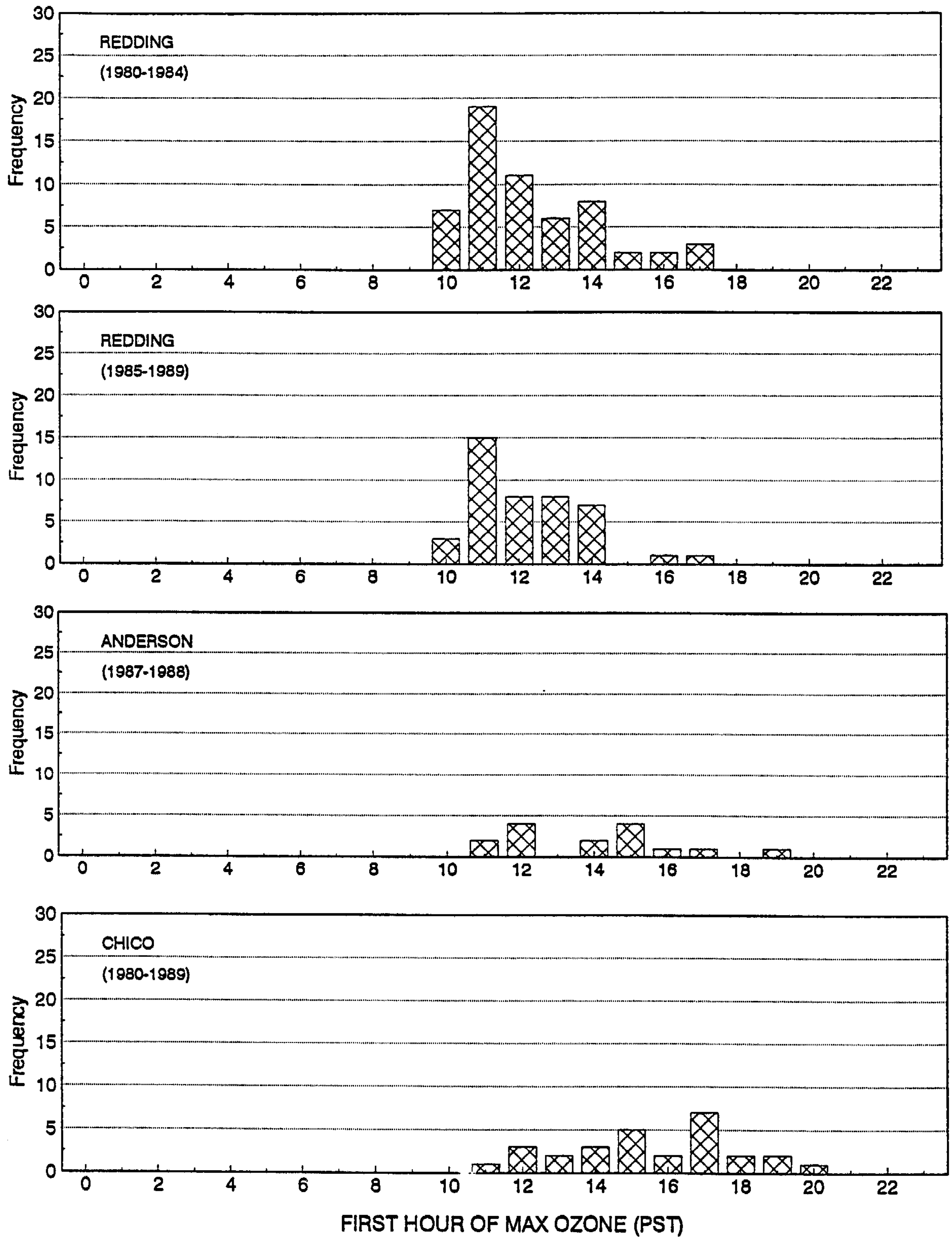


Figure 2-8. Frequency of First Hour of Maximum Ozone Concentration on State Exceedance Days at Redding, Anderson, and Chico.

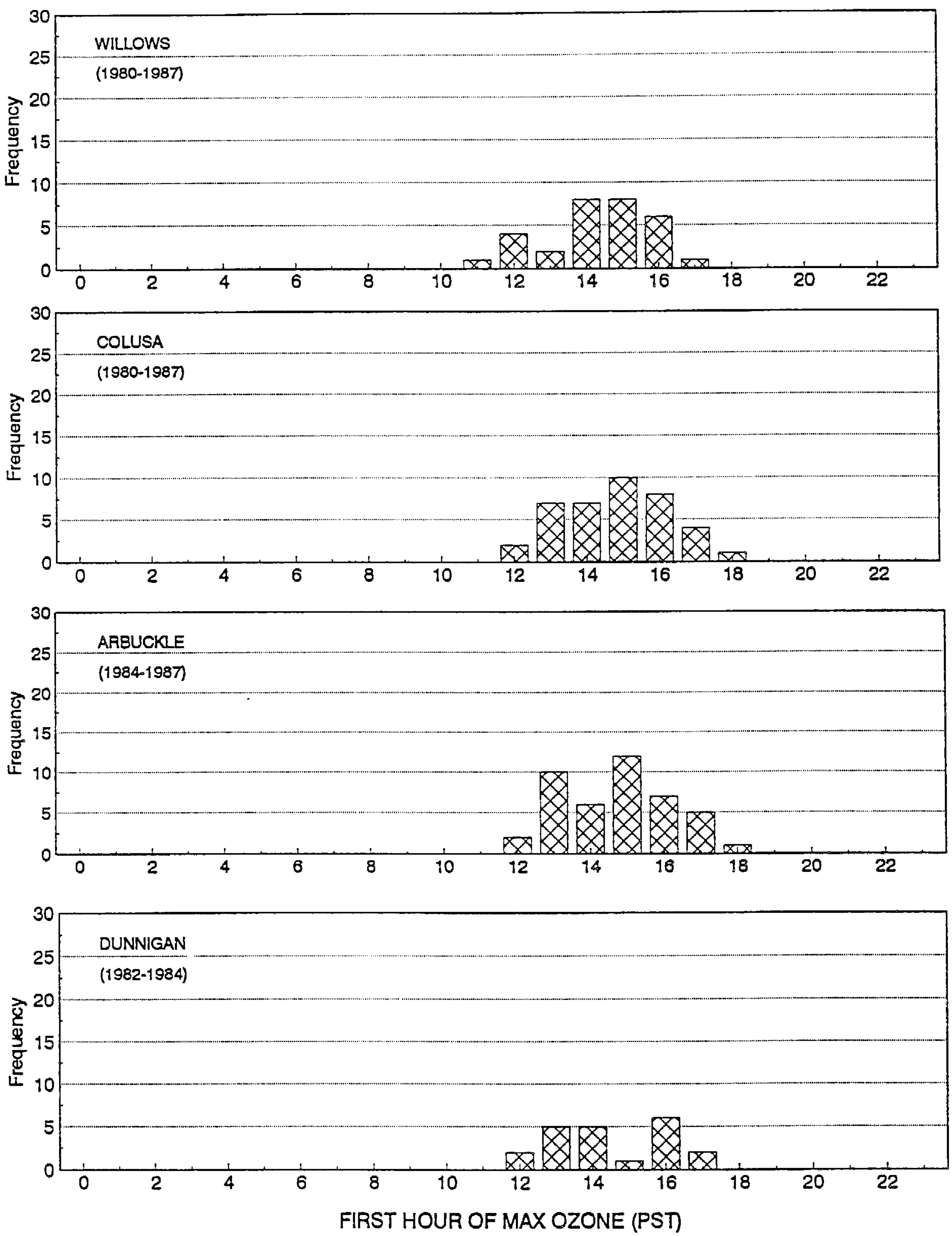


Figure 2-9. Frequency of First Hour of Maximum Ozone Concentration on State Exceedance Days at Willows, Colusa, Arbuckle, and Dunnigan.

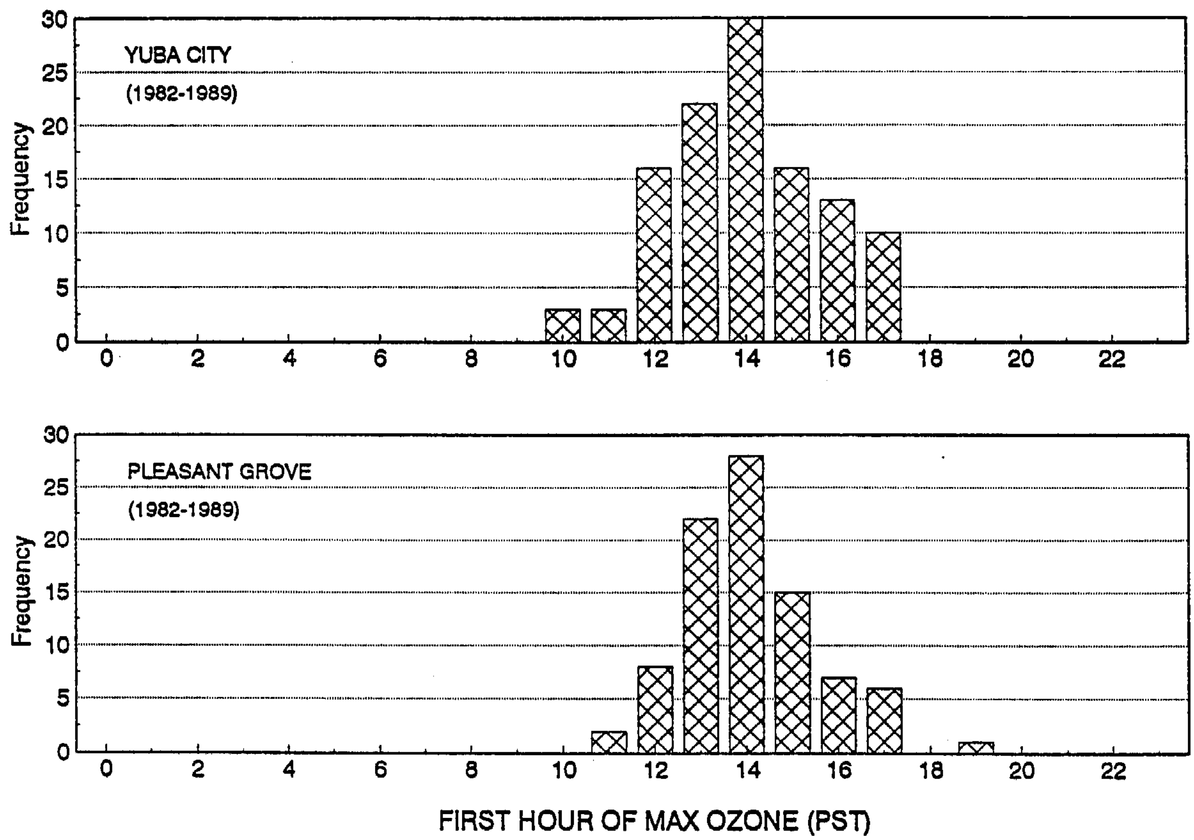


Figure 2-10. Frequency of First Hour of Maximum Ozone Concentration on State Exceedance Days at Yuba City and Pleasant Grove.

- Acquired wind speed and wind direction data to cover the potential transport paths from the upwind air basin(s) to the downwind air basin; evaluate the data for appropriateness for subsequent analyses. In most cases, only surface wind data were available. In a few cases, sufficient upper air wind data were also available.

- Generated hourly wind fields for the periods of interest and use the wind fields to calculate air-parcel trajectories. If upper air data were available, we also prepared aloft wind fields and trajectories. Backward air-parcel trajectories were calculated for periods of high ozone concentrations at receptor sites. These trajectories were used to determine the general path that an arriving air parcel might have followed on its way to the receptor monitoring site. We also calculated some forward trajectories for periods of high emissions in the potential source areas. These trajectories were used to determine the general path that a polluted air parcel might have followed on its way from the source area.

- Prepared a consensus of the trajectory analysis for each receptor area. We used the individual results of a large number of backward and forward trajectories to develop the consensus trajectory (or trajectories) for each receptor. Rather than use an individual trajectory for one exceedance day, we developed this consensus using many trajectories to increase the probability that the correct transport path would be represented.

- Evaluated the results of the trajectory analysis and compared the results with meteorological and air quality data along the potential transport path. This task included simple analyses to see if wind speed/direction and peak ozone concentrations are consistent with transport along that route. In some cases, we also examined the timing of peak ozone concentrations along potential transport paths; a sequence of ozone peaks that fit general transport times (using wind speed, for example) would indicate transport.

- Prepared some simple pollutant flux plots in order to better understand when transport occurred and how much ozone and NO_x were being transported. We calculated a simple relative pollutant flux by multiplying the hourly pollutant concentration by the hourly wind speed in the transport direction.

To develop hourly wind fields for violation days, we used the Caltech 2-D wind interpolation procedure, as modified and documented by Dr. Kit Wagner of the Technical Support Division of the ARB. For surface wind fields, the procedure used hourly-averaged wind speed and direction data from a large number of surface monitoring sites in each area, including data from the following major sources:

- The California Air Resources Board (ARB);

- Weather Network, Inc. for the Sacramento Valley;

- The Sacramento Area Ozone Study (sponsored in the summers of 1989 and 1990 by the Sacramento Area Council of Governments);

- The Upper Sacramento Transport Study (sponsored in the summer of 1990 by the ARB);

- The Bay Area Air Quality Management District (BAAQMD) 10-meter tower network;

- The San Joaquin Valley Air Quality Study and AUSPEX (SJVAQS/AUSPEX) for the summer of 1990 (these data were validated to Level Ib);

- The National Ocean Buoy Center for data collected offshore of northern California by the Minerals Management Service, the U.S. Coast Guard, the Army Corps of Engineers, and the National Weather Service (NWS); and

- The CIMIS network. Since these data are collected at about two meters, wind speeds are often slower than at higher altitudes; we only used CIMIS data from locations where other data were not available (Greenfield in the Salinas Valley, for example).

For a few days during 1989 and 1990, sufficient upper air wind data were available to compute aloft wind fields for much of the Sacramento Valley area. For these days, we obtained upper air wind speed and direction data for intensive sampling days from the Sacramento Area Ozone Study during the summer of 1989 (four soundings per day at seven sites, see Prins, et al., 1990, and Prins and Prouty, 1990) and 1990 (six soundings per day at four sites, see Prins and Prouty, 1991a and 1991b), and the Upper Sacramento Transport Study for the summer of 1990 (four soundings per day at two sites, see Prins and Prouty, 1991c and 1991d), plus corresponding data from the NWS twice-daily soundings at the Oakland Airport. The data were interpolated to each hour between soundings. We also used hourly data from two Doppler acoustic sounders operated for the 1990 SJVAQS/AUSPEX (these data were validated to level Ib).

The wind field procedure used a 10 km by 10 km grid which covered the area of interest, including the downwind receptor area and the upwind source area(s) (see maps in the individual sections). The trajectories were generated using the hourly wind field at 30-minute time steps. Back trajectories were generated for peak ozone hours on ozone violation days at important monitoring sites in the Upper Sacramento Valley and North Central Coast monitoring sites. Ensembles of trajectories defined typical transport paths on violation days.

2.2.2 Trajectory Results Using Surface Data

To evaluate transport to the Upper Sacramento Valley, we selected the domain shown in Figure 2-11. This domain included the receptor sites in the Upper Sacramento Valley and the two upwind air basins, the Broader Sacramento area and the San Francisco Bay Area. We also included the northern part of the San Joaquin Valley in order to complete the wind flow patterns out of the Bay Area and into both the Sacramento and San Joaquin Valleys. We used wind data from 85 surface wind measurement sites. The sites are shown on the map

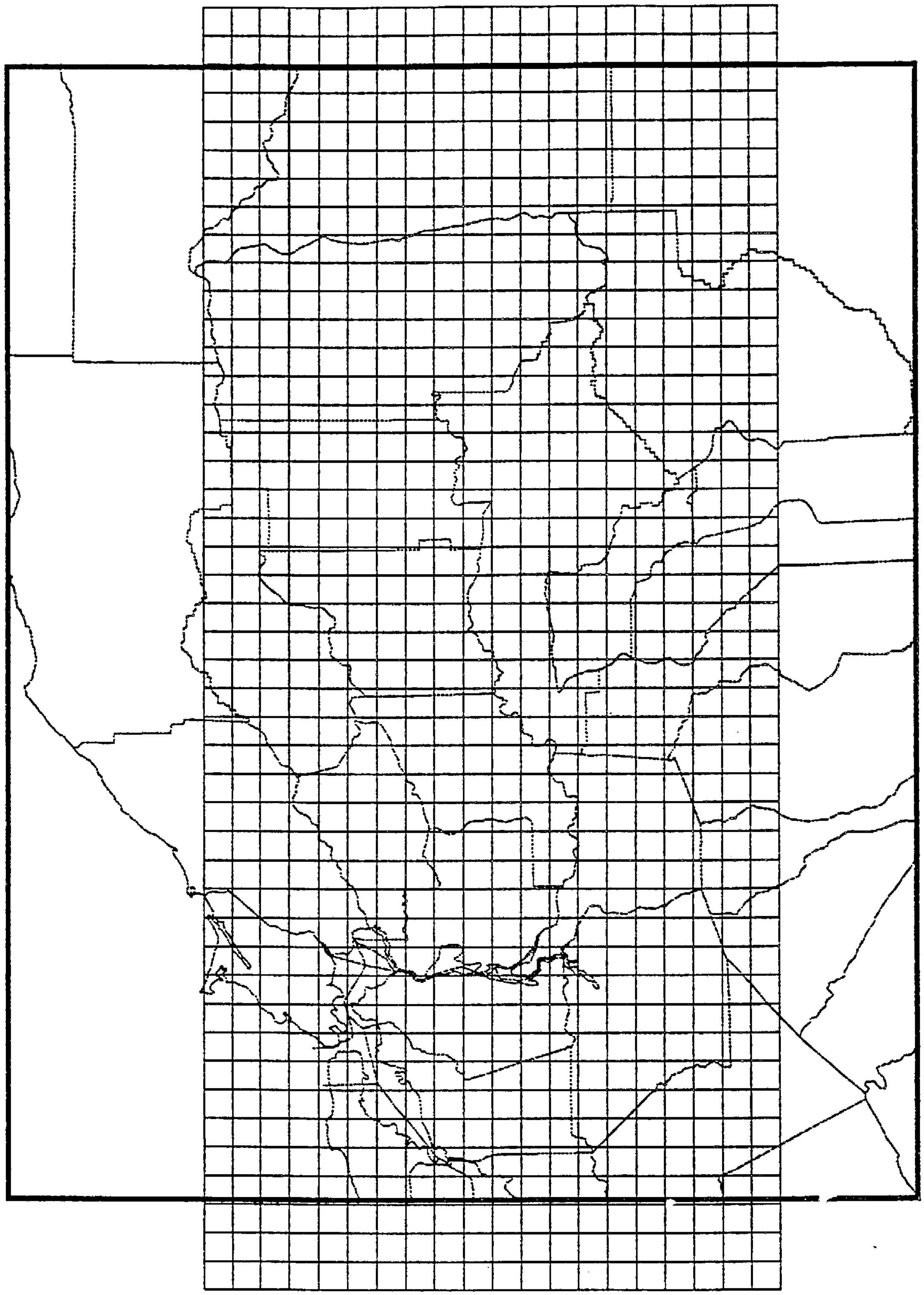


Figure 2-11. Map Showing Wind Field Grid for Upper Sacramento Valley Trajectories.

in Figure 2-12 and listed with UTM coordinates in Table 2-2. Data for a few of these sites are limited in duration, such as those sites operated for the SACOG field studies in 1989 and 1990.

Based on the results in Section 2.1.2, we selected ozone exceedance days from the 1987-1990 period. The selections were based on days with the highest ozone concentrations at Upper Sacramento Valley monitoring sites, plus the availability of surface and aloft meteorological data.

We prepared surface wind fields for the Northern California domain for 86 days, 34 in 1987, 17 in 1988, 24 in 1989, and 11 in 1990. We then estimated forward and backward trajectories for selected locations and times. We prepared a total of 1144 forward and backward surface trajectories. The following discussion illustrates the general characteristics of those trajectories and summarizes the transport results.

Figures 2-13 through 2-17 illustrate various characteristics of the Upper Sacramento Valley trajectories. These trajectories are for 1987, the most recent year when many ozone exceedances were recorded in the Upper Sacramento Valley. These trajectories were prepared using surface winds only; no aloft Sacramento Valley wind data are available to use for 1987 trajectories. If both surface and aloft trajectories were available, some of the conclusions discussed below might be modified. Some examples using both surface and aloft trajectories will be covered in the next subsection.

Figure 2-13 shows back trajectories from Redding, Red Bluff, and Chico for 1600 PST on June 26, 1987; the trajectories for 1200 and 1400 PST were similar. On that day, maximum ozone concentrations were 13 pphm at Redding and 10 pphm at Chico, the highest of the year. The exact location of the air parcel history is inaccurate when the wind speeds are low, as in these examples. However, the general conclusion is still valid: that the air parcels were in the local area for the previous day or two.

Figures 2-14 and 2-15 show back trajectories from Redding, Red Bluff, and Chico for 1200 PST on July 14, 1987 and on July 15, 1987; the trajectories for 1400 and 1600 PST on each day were similar to the ones shown. The maximum ozone concentrations on those days were 11 and 10 pphm, respectively at Redding, and 8 and 9 pphm at Chico. The trajectories show slow transport back down the Sacramento Valley, with some trajectories reaching the SFBAAB. The July 14 Redding trajectory indicates that the air parcel had been in the Redding area since the night before, but had been transported up the valley on the previous day. This illustrates how pollutant carryover might contribute to an ozone exceedance at Redding. The July 15 Redding trajectory shows more-direct transport up the valley.

Figures 2-16 and 2-17 show a different sequence for August 7 and 8, 1987. The only exceedance on August 7 was at Chico (10 pphm maximum at 1700 PST); an 11 pphm maxima was measured at Redding on the 8th. The August 7, 1987 1600 PST Red Bluff and Chico trajectories show transport from down the valley, while the Redding trajectory shows transport from the north; the trajectories for 1200 and 1400 PST were similar. This shows evidence of a convergence zone between Redding and Red Bluff which separates the northern part of the Upper Sacramento Valley from emissions sources to the south; this convergence zone is often evident on the ARB wind flow charts. The

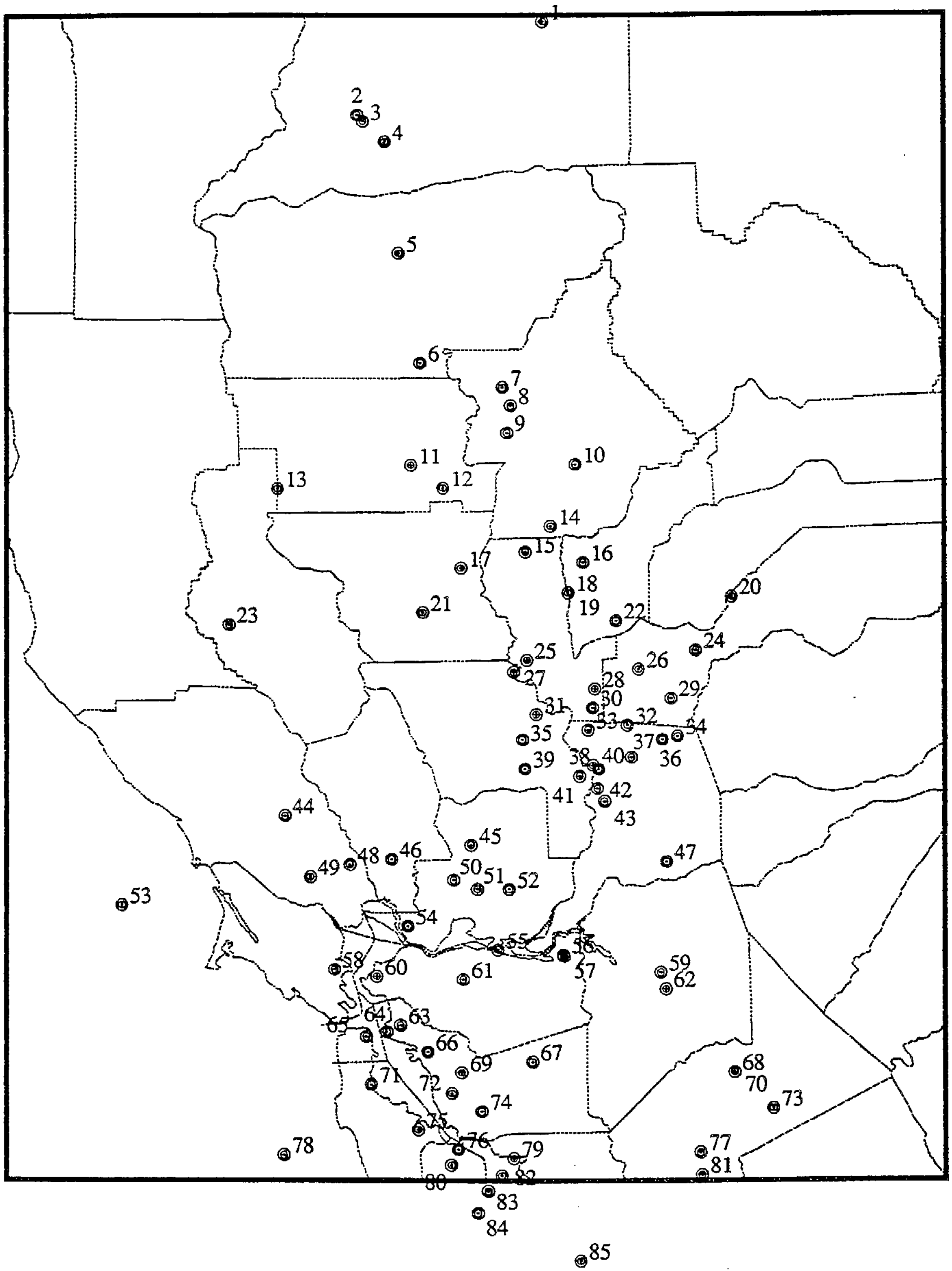


Figure 2-12. Map Showing Surface Wind Sites for Upper Sacramento Valley Trajectories.

Table 2-2. Wind Sites for Upper Sacramento Valley Trajectories, Including Site Number (See Figure 2-12) and UTM Coordinates

No.	UTM-E	UTM-N	Name
1	612061.	4526857.	Burney
2	550000.	4495000.	Redding airport
3	551955.	4492859.	Redding-1615 Continental
4	559296.	4485710.	Redding (NOAA)
5	563861.	4446895.	Red Bluff (NOAA)
6	571278.	4409554.	CAPAY
7	598685.	4401311.	Chico Manzinita
8	601422.	4395130.	CHICO ST. FARM
9	600170.	4385900.	DURHAM
10	623180.	4375131.	OROVILLE
11	568075.	4374895.	Willows
12	578900.	4367117.	CODORA
13	522973.	4366750.	BIGGS
14	614894.	4354023.	Gridley
15	606393.	4345245.	SUTTER BUTTES
16	625800.	4341600.	NORTH YUBA
17	584963.	4339765.	Colusa
18	620727.	4331258.	Yuba City-Ag Building
19	620763.	4331245.	Yuba City
20	676012.	4329823.	Colfax
21	572063.	4324542.	ARBUCKLE
22	637015.	4321631.	WHEATLAND
23	506423.	4320223.	Lakeport-Lakeport Blvd
24	663948.	4311558.	Auburn-Dewitt Center
25	606894.	4308289.	Kirkville
26	644590.	4305114.	LINCOLN
27	602500.	4304200.	Tyndall Mound (SACOG)
28	629863.	4298420.	Pleasant Grove
29	655626.	4295168.	Rocklin-Sierra College
30	629096.	4291958.	Pleasant Grove-4SW
31	610099.	4289797.	DIXON
32	640852.	4286115.	North Highlands-Blackfoot
33	627568.	4284508.	NATOMAS
34	657823.	4282299.	Folsom
35	605432.	4281187.	Woodlands
36	652685.	4281175.	Citrus Hts - Sunrise
37	642193.	4275199.	Sacramento-Del Paso Manor
38	629263.	4272436.	Broderick
39	606260.	4271320.	Davis Golf Course
40	631180.	4271135.	Sacramento 1131 S St.
41	624700.	4268800.	West Sacramento (SACOG)
42	630764.	4264579.	Sacra. Exec. Airport (NOAA)
43	633160.	4260225.	Sacramento-Meadowview Rd
44	525474.	4255283.	Santa Rosa-837 Fifth St
45	588385.	4245491.	Vacaville-Merchant

Table 2-2. Wind Sites for Upper Sacramento Valley Trajectories, Including Site Number (See Figure 2-12) and UTM Coordinates

Page 2 of 2

No.	UTM-E	UTM-N	Name
46	561637.	4240601.	Napa-Jefferson Street
47	654100.	4239700.	Herald (SACOG)
48	547521.	4238789.	Sonoma-First Street
49	534100.	4234500.	PETALUMA
50	582548.	4233539.	Fairfield-Bay Area APCD
51	590500.	4230500.	Scalley Road (SACOG)
52	601000.	4230500.	Lambie Road (SACOG)
53	470000.	4225000.	MMS BOUY 46013
54	567087.	4217629.	Vallejo-Tuolumne
55	597225.	4209667.	Pittsburg
56	619302.	4207907.	Bethel Island
57	619400.	4207400.	Bethel Island-ARB TELEMETRY
58	542246.	4202841.	San Rafael
59	652101.	4201793.	Stockton-Hazelton Street
60	556606.	4200448.	Richmond-13th Street
61	585715.	4199430.	Concord-2975 Treat Blvd
62	653860.	4196164.	Stockton (NOAA)
63	564539.	4183786.	Oakland-Alice
64	559881.	4181624.	Alameda NAS (NOAA)
65	553012.	4180017.	San Francisco-10 Arkansas
66	573801.	4174900.	San Leandro
67	608793.	4171599.	Livermore-Old First St
68	676983.	4167988.	Modesto
69	585185.	4167953.	Hayward-La Mesa
70	677002.	4167945.	Modesto-814 14th Street
71	554715.	4163835.	San Francisco Airport (NOAA)
72	581900.	4160900.	UNION CITY
73	689977.	4155765.	Turlock-Monte Vista
74	591851.	4154800.	Fremont-Chapel Way
75	570489.	4148552.	Redwood City
76	584061.	4141889.	Moffet Field (NOAA)
77	665518.	4140888.	Crows Landing (NOAA)
78	525000.	4140000.	MMS BOUY 46012
79	602475.	4138966.	San Jose-Piedmont Road
80	581700.	4136703.	Mountain View-Cuesta
81	666061.	4133311.	Crows Landing-Davis Road
82	598501.	4133171.	San Jose - 4th St.
83	594000.	4128000.	PG&E SUBSTATION IN CAMPBELL
84	590601.	4120520.	Los Gatos
85	625000.	4104400.	SAN MARTIN

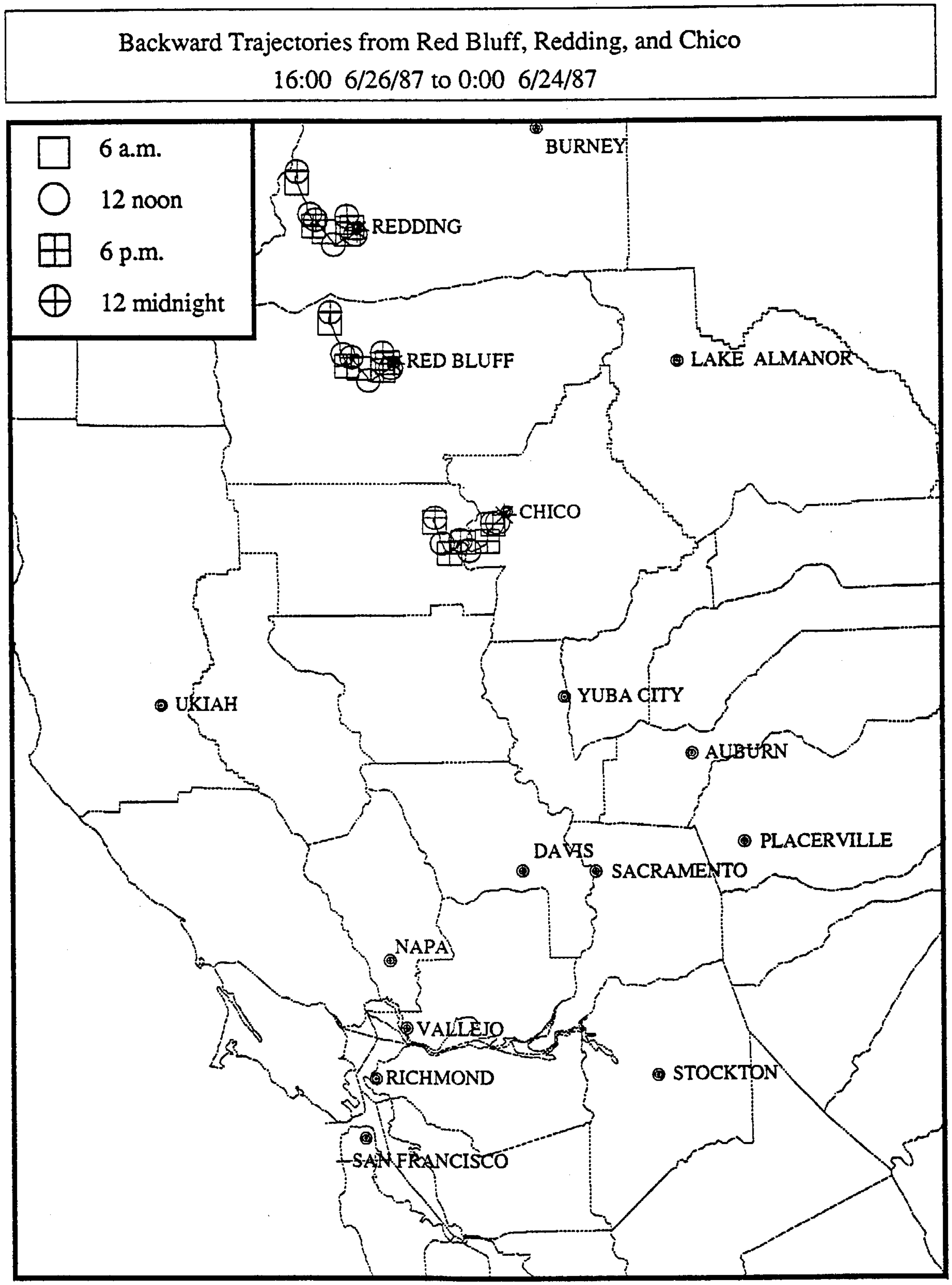


Figure 2-13. Surface Back Trajectories From Red Bluff, Redding, and Chico on June 26, 1987 Beginning at 1600 PST.

Backward Trajectories from Red Bluff, Redding, and Chico
12:00 7/14/87 to 0:00 7/12/87

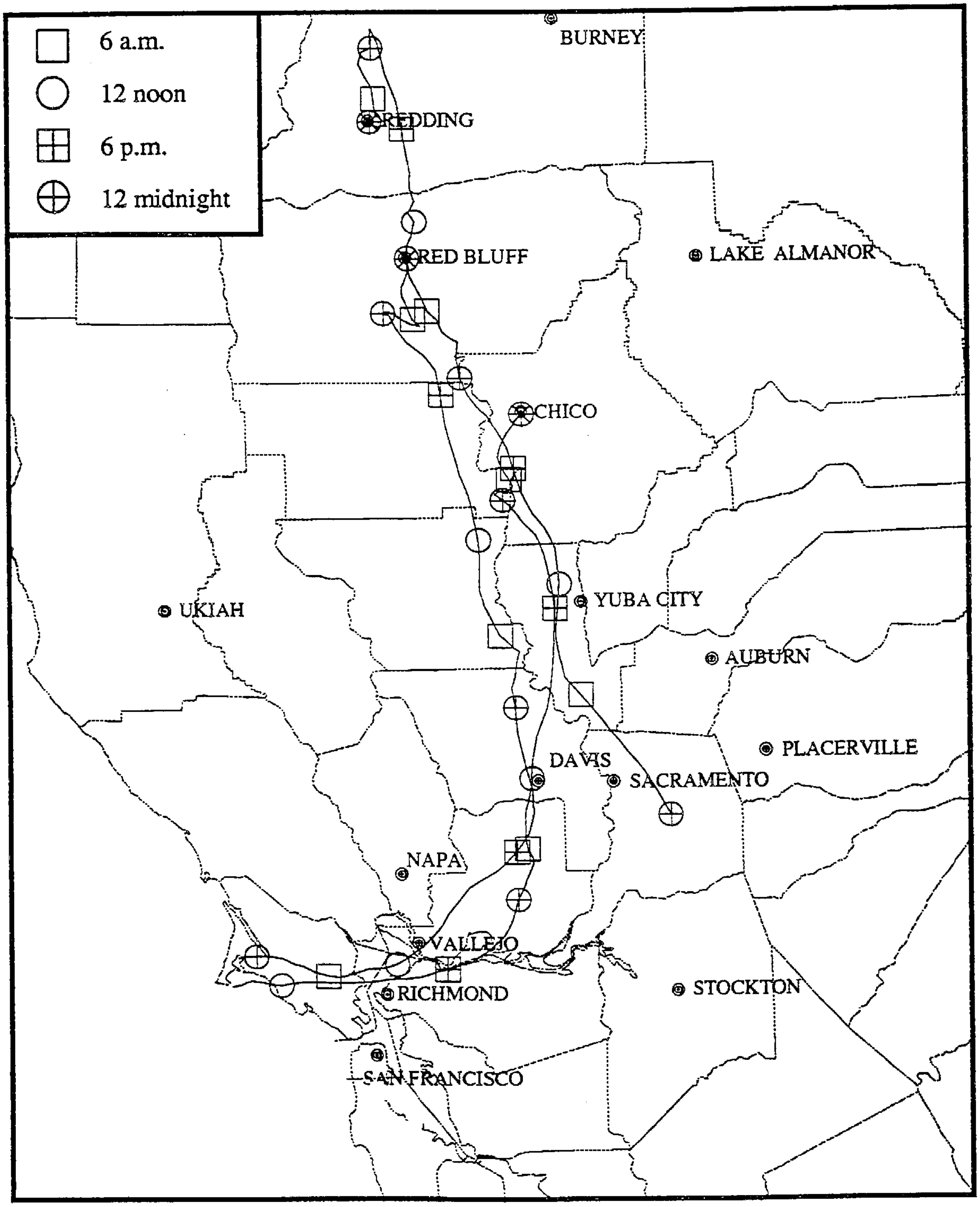


Figure 2-14. Surface Back Trajectories From Red Bluff, Redding, and Chico on July 14, 1987 Beginning at 1200 PST.

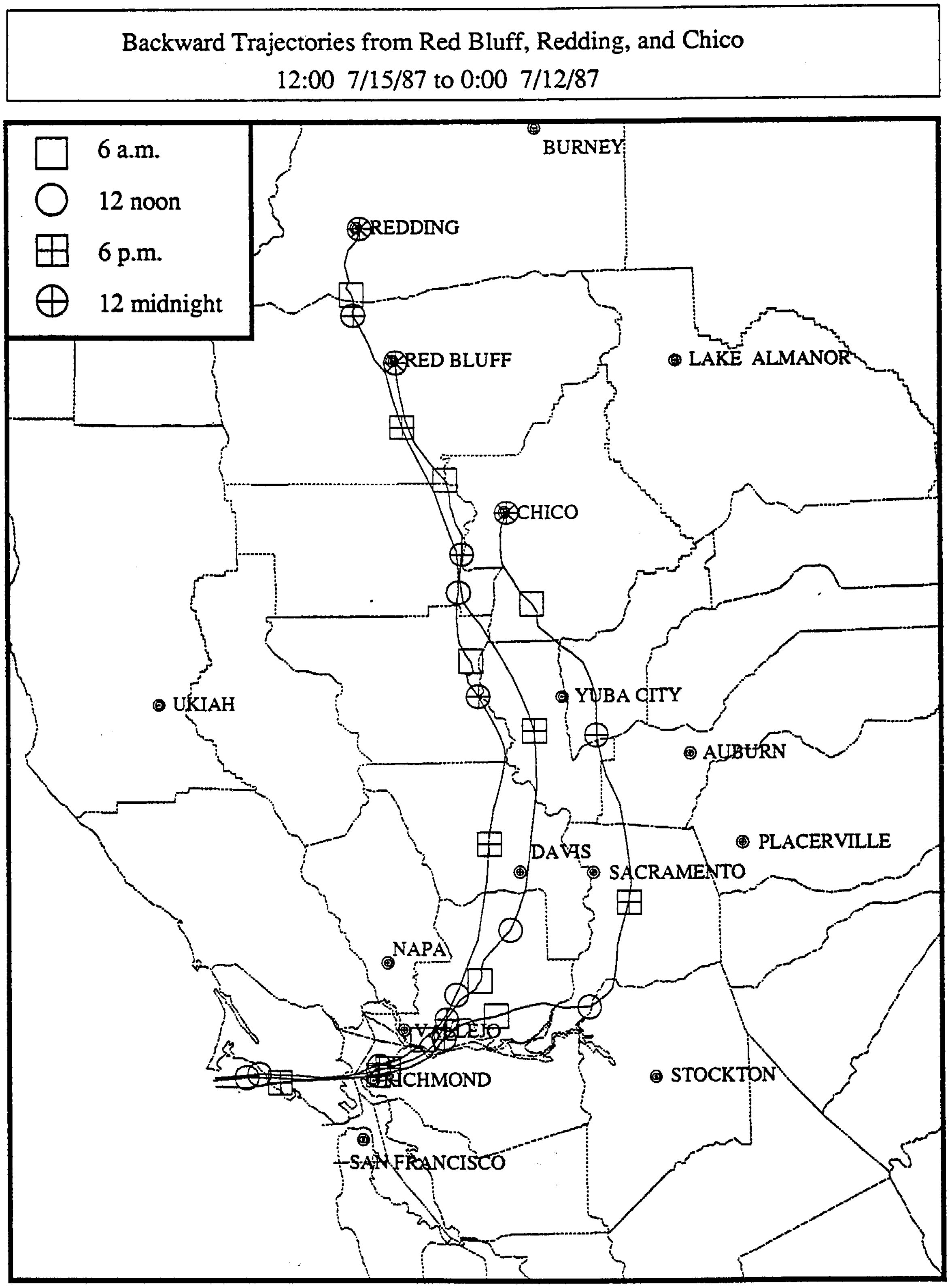


Figure 2-15. Surface Back Trajectories From Red Bluff, Redding, and Chico on July 15, 1987 Beginning at 1200 PST.

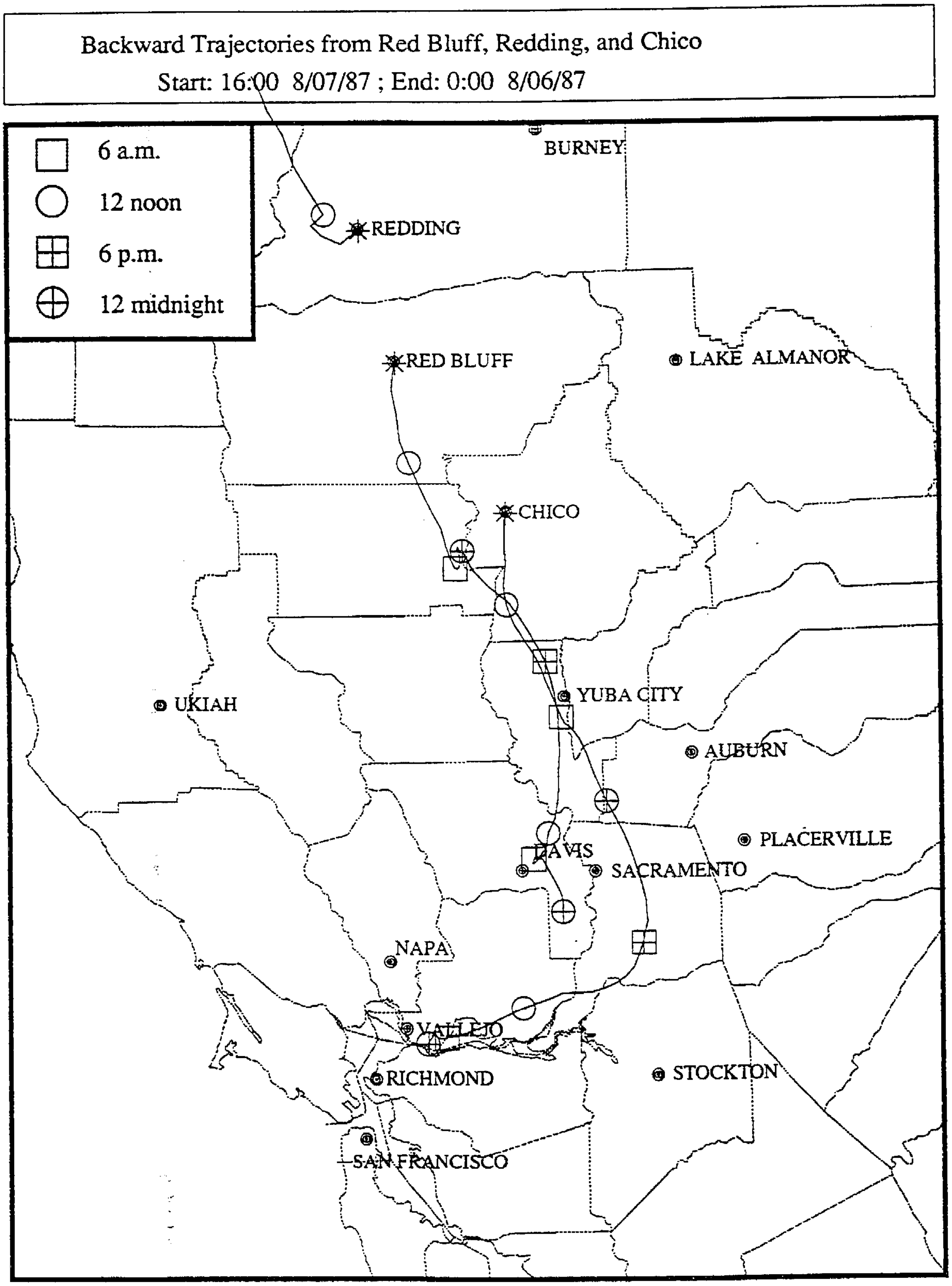


Figure 2-16. Surface Back Trajectories From Red Bluff, Redding, and Chico on August 7, 1987 Beginning at 1600 PST.

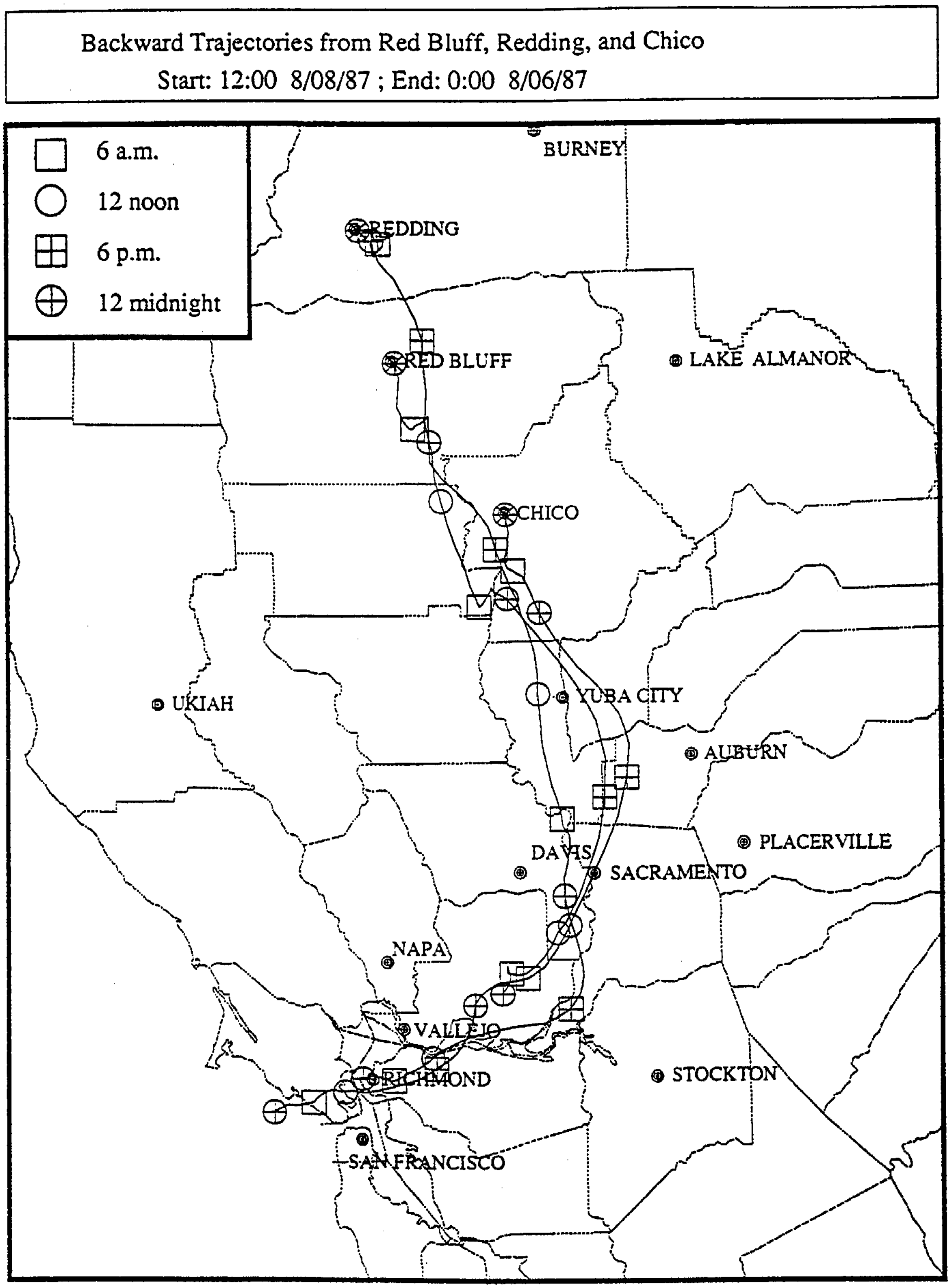


Figure 2-17. Surface Back Trajectories From Red Bluff, Redding, and Chico on August 8, 1987 Beginning at 1200 PST.

convergence zone can be further south than Red Bluff on many days, especially in the morning, but this day is an illustration that it can completely block transported pollutants from reaching Redding, at least at the surface.

The August 8, 1987 trajectories from Red Bluff and Chico shown in Figure 2-17 are similar to the previous day, but the Redding air parcel had arrived from the south. The Redding trajectory indicates that the air parcel had reached an area south of Redding late the previous evening. This is another illustration of how pollutant carryover might contribute to an ozone exceedance at Redding.

2.2.3 Trajectory Results Using Aloft Data

Trajectories were estimated at aloft levels in order to evaluate potential influence of aloft transport on surface ozone concentrations. The 400 meter level was chosen to represent a typical polluted air parcel within the daytime mixed layer; the 800 meter level was chosen to represent an air parcel near the top of or above the daytime mixed layer. Transport winds aloft are typically much faster than those at the surface, especially at night.

Aloft meteorological data are available for several locations in the Sacramento Valley, plus at the Oakland Airport on August 3-5, 1989; July 11-13, 1990; and August 7-10, 1990. During the 1989 period, aloft meteorological data are available every six hours at seven sites in the Broader Sacramento area (Prins, et al., 1990, and Prins and Prouty, 1990). The northern-most sites were near Kirkville, and at Nicolas and Lincoln. During the July 1990 period, aloft meteorological data were available every four hours at four sites in the Broader Sacramento area (Prins and Prouty, 1991a and 1991b), plus every six hours at two sites in the Upper Sacramento Valley (Prins and Prouty, 1991c and 1991d). The northern-most sites were at Maxwell and about 10 km northeast of Yuba City. During the August 1990 period, data are available only from the four Broader Sacramento sites (Prins and Prouty, 1991a and 1991b).

We prepared 400 and 800 meter wind fields for August 3-5, 1989, August 15-16, 1989, and July 11-13, 1990. Because of fewer sites, we prepared only 400 meter wind fields for August 7-10, 1990. We then estimated forward and backward trajectories for selected locations and times. We prepared a total of 177 forward and backward trajectories. The following discussion illustrates the general characteristics of those trajectories and summarizes the transport results.

Figures 2-18, 2-19, and 2-20 show back trajectories from Chico on August 5, 1989 at 1600 PST using surface, 400 meter, and 800 meter winds, respectively. Maximum ozone concentrations were 8 pphm at Redding and 9 pphm at Chico. The surface and 400 meter trajectories show a consistent path back through the Broader Sacramento area and the San Francisco Bay Area. However, the speed of the transport is much different; the surface trajectory shows much slower transport than the 400 meter one, more than two days from the Bay Area versus less than a day. The 800 meter trajectory indicates transport

Backward Trajectory from Chico
16:00 8/05/89 to 0:00 8/01/89

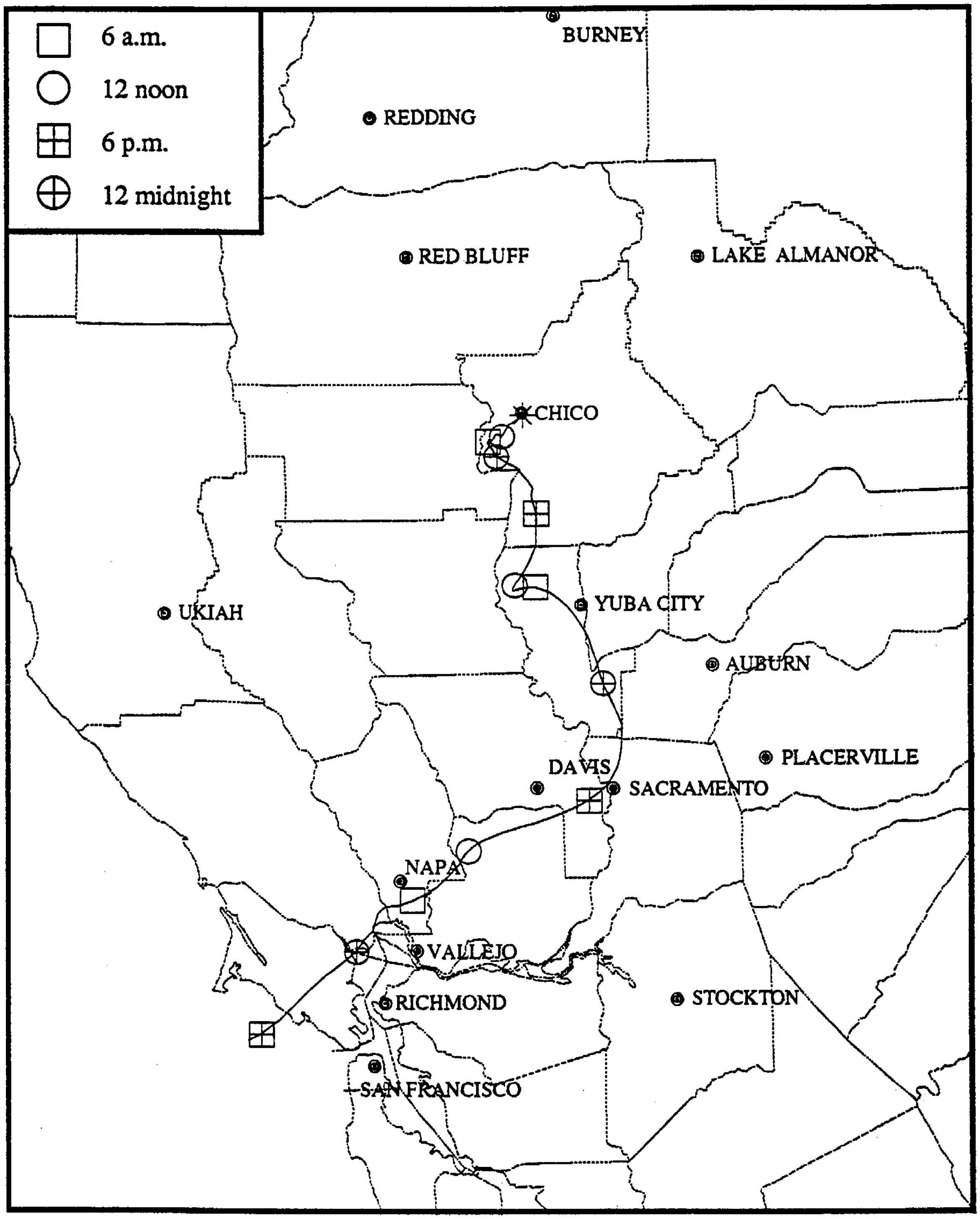


Figure 2-18. Surface Back Trajectory From Chico on August 5, 1989 Beginning at 1600 PST.

Backward Trajectory from Chico

16:00 8/05/89 to 0:00 8/03/89

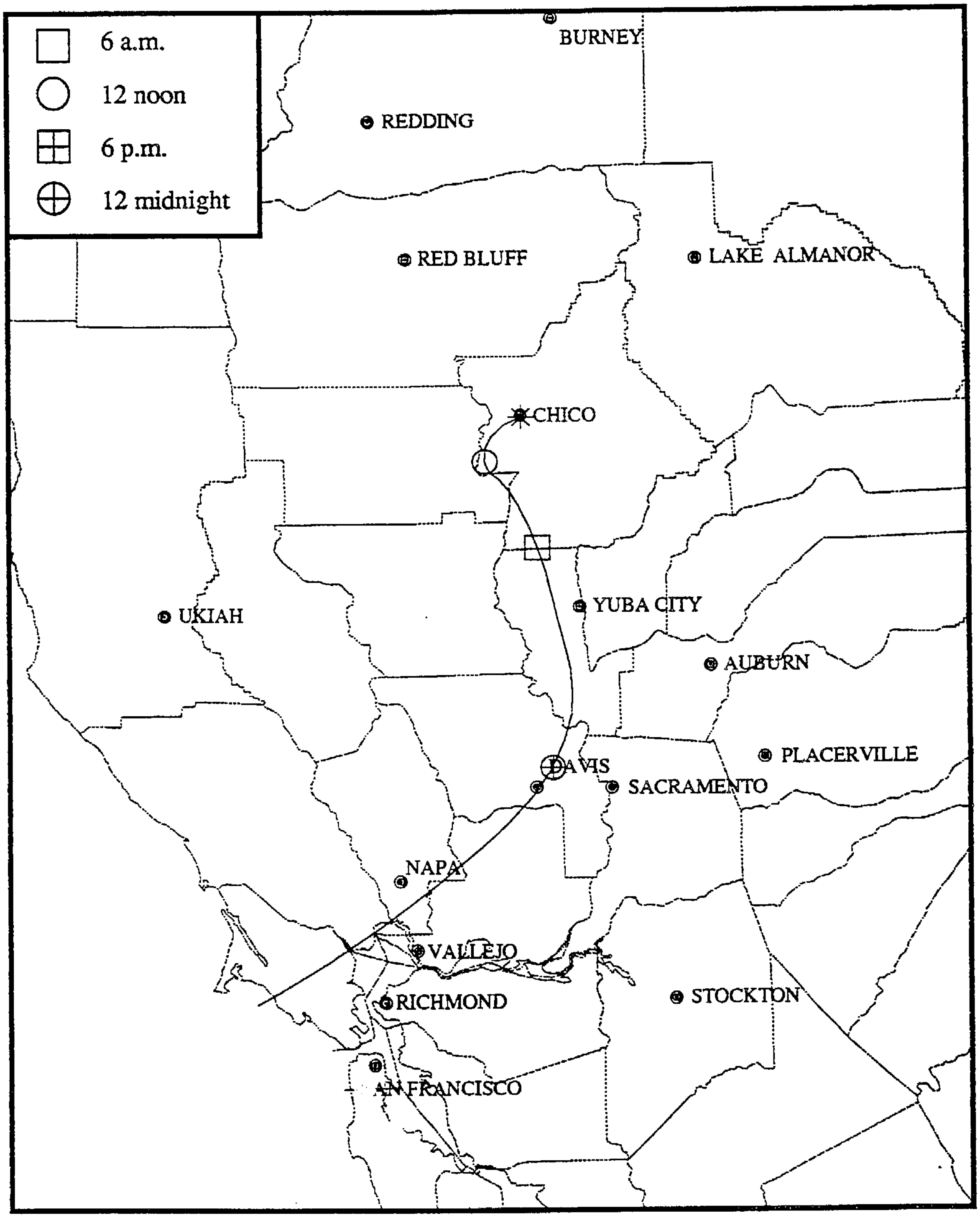


Figure 2-19. Aloft 400 Meter Back Trajectory From Chico on August 5, 1989 Beginning at 1600 PST.

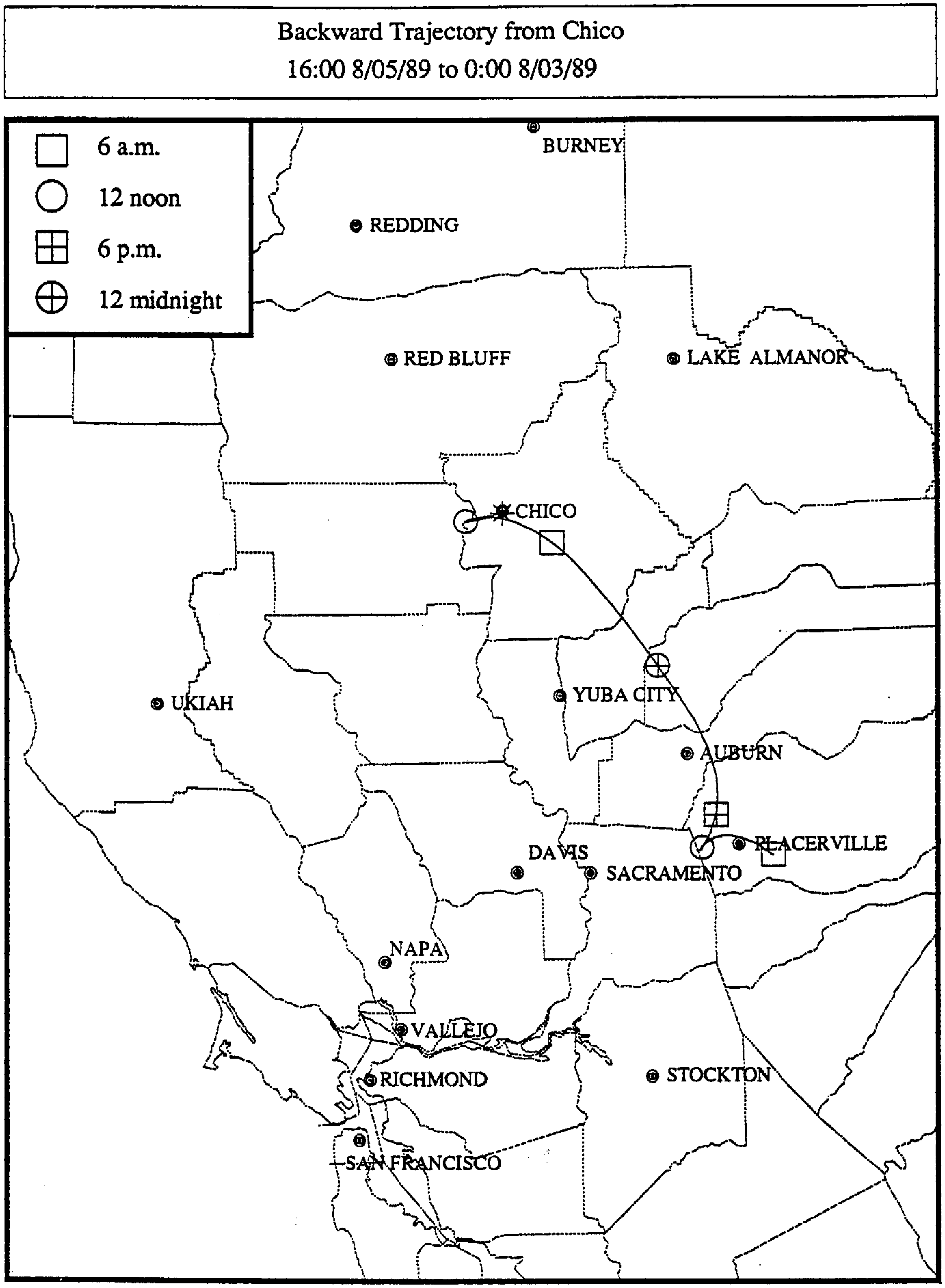


Figure 2-20. Aloft 800 Meter Back Trajectory From Chico on August 5, 1989 Beginning at 1600 PST.

back to the area east of Sacramento in 20-36 hours. These results are similar to those for the other two 1989 days on which we have aloft data: August 4 and 16.

The aloft trajectories which we have estimated have a major limitation: the lack of data in the northern part of the Sacramento Valley. For the July 11-13, 1990 period, the northern-most upper air sites were at Maxwell and a location about 10 km northeast of Yuba City. For 1989 and the August 7-10, 1990 period, the northern-most upper air sites were at Kirkville and Lincoln. Maxwell is about 55 km south of Chico; Kirkville and Lincoln about 90 km; Maxwell is over 130 km from Redding. On a day without a convergence zone in the Upper Sacramento Valley, the wind data within the mixed layer at Maxwell, for example, may be similar to the actual winds further north toward Red Bluff and Redding. In this case, the uncertainty in air parcel location will be larger than in an area where data exists, but possibly still acceptable for qualitative use. However, on a day with a convergence zone, the wind data within the mixed layer at Maxwell south of the convergence zone is probably very dissimilar to the winds north of the convergence zone, including the area around Redding. In this case the uncertainty would be unacceptable. Thus, we did not use results from any Redding aloft trajectories if there was a convergence zone present.

During 1990, aloft data are available for July 11-13 and August 7-10. The highest ozone concentrations at Upper Sacramento Valley sites during the July 11-13 period were at Redding (9 pphm) and at Chico (8 pphm) on July 13. Surface back trajectories for Chico, Red Bluff, and Redding on the 13th had been within about 50-75 km of their ending locations for the previous two days. Aloft trajectories had been within about 50-75 km of their ending locations for the previous day, then went back to the northwest. Several forest fires in the area north and northeast of Chico further complicate a consistent interpretation of this episode.

During the August 7-10, 1990 period, maximum ozone concentrations were 13 pphm at Redding on the August 7, 12 pphm at Chico on August 8, and 13 pphm at Chico on August 9 (see Figure 2-21). On August 7 notice the almost straight-line rise in ozone concentrations to a sharp peak at 1200 PST, a typical time for a Redding peak. We will use surface and aloft trajectories for Redding and Chico to illustrate the pollutant transport on these days.

Figure 2-22 shows the Redding surface back trajectories for 1200, 1400, and 1600 PST on this day. The 1200 and 1400 PST surface trajectories indicate that the air parcel had arrived in the Redding area from the north late on the previous day. These trajectories probably represent the air parcels arriving during the peak ozone concentration. However, notice that the 1600 PST trajectory indicates arriving air parcels which had been in the Chico area on the previous day.

The aloft trajectory analysis shows fast-moving air parcels arriving from the south. Figure 2-23 shows aloft 400 meter trajectories for this day. Notice how the Redding aloft back trajectory does not follow the Sacramento Valley to the southsoutheast, but arrives from the southsouthwest across the coast range. The forward trajectory from Howe Park does the opposite: it travels almost due north on August 7 and arrives at about the Redding latitude

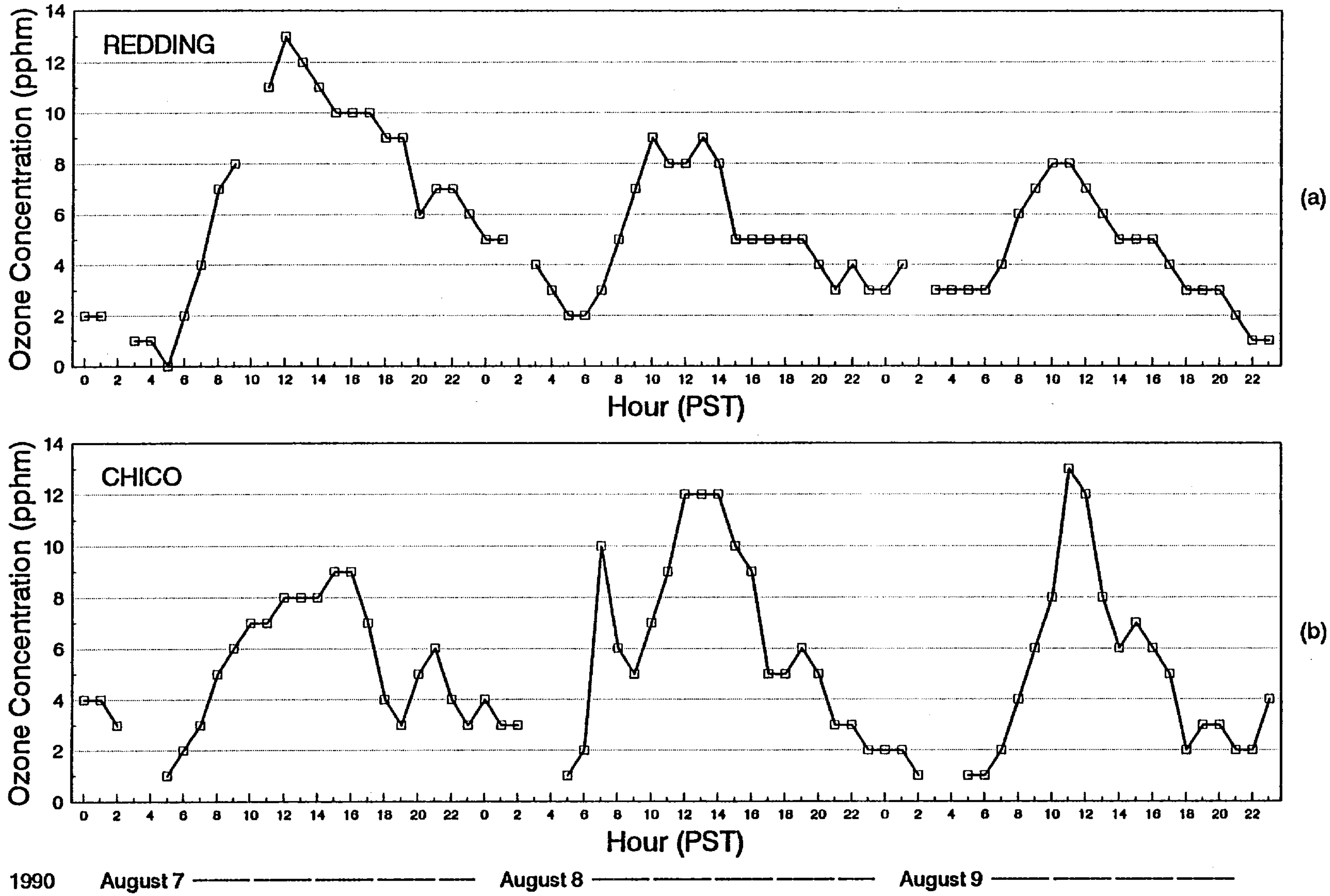


Figure 2-21. Hourly Ozone Concentrations at Redding and Chico on August 7-9, 1990.

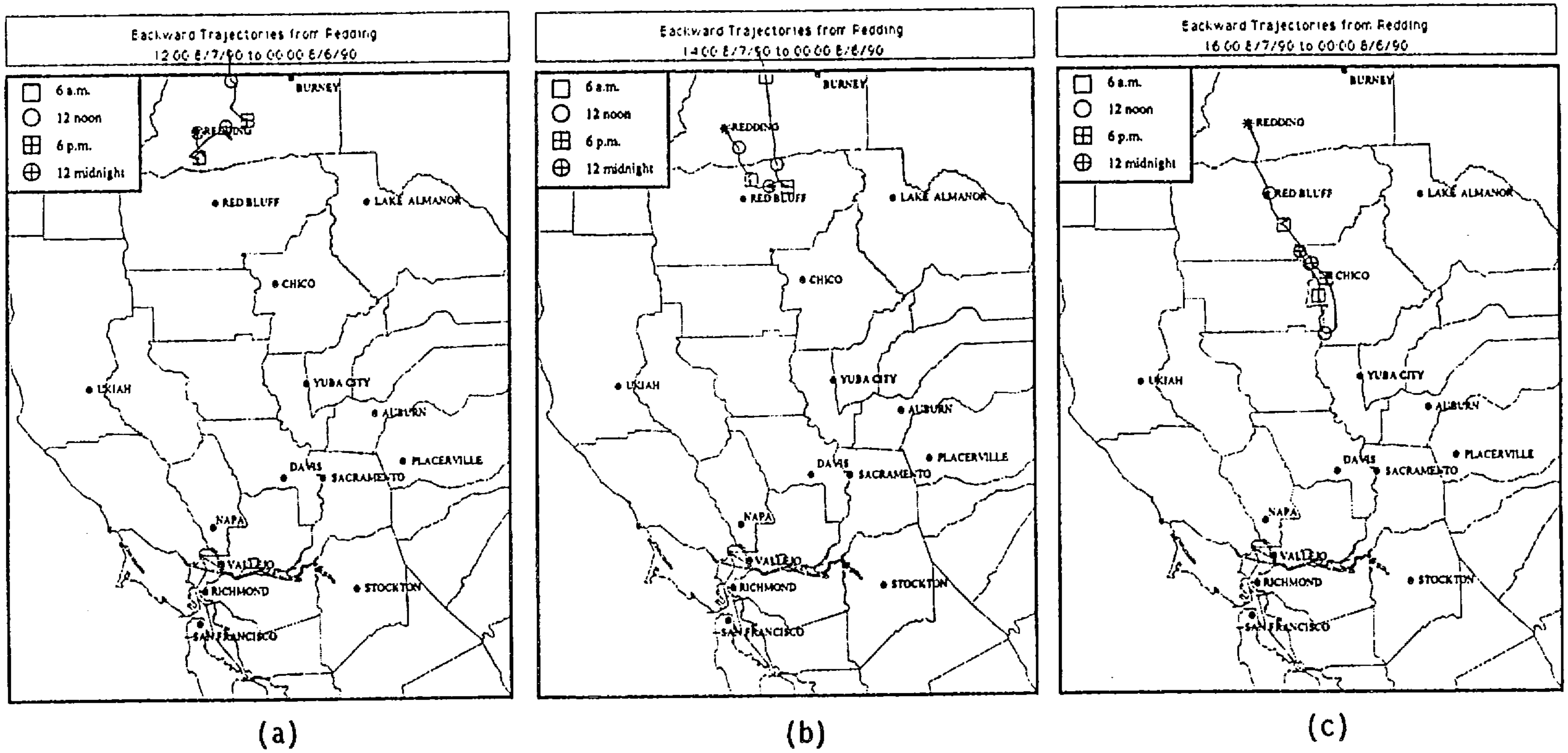


Figure 2-22. Surface Back Trajectories From Redding on August 7, 1990 Beginning at 1200 (a), 1400 (b), and 1600 (c) PST.

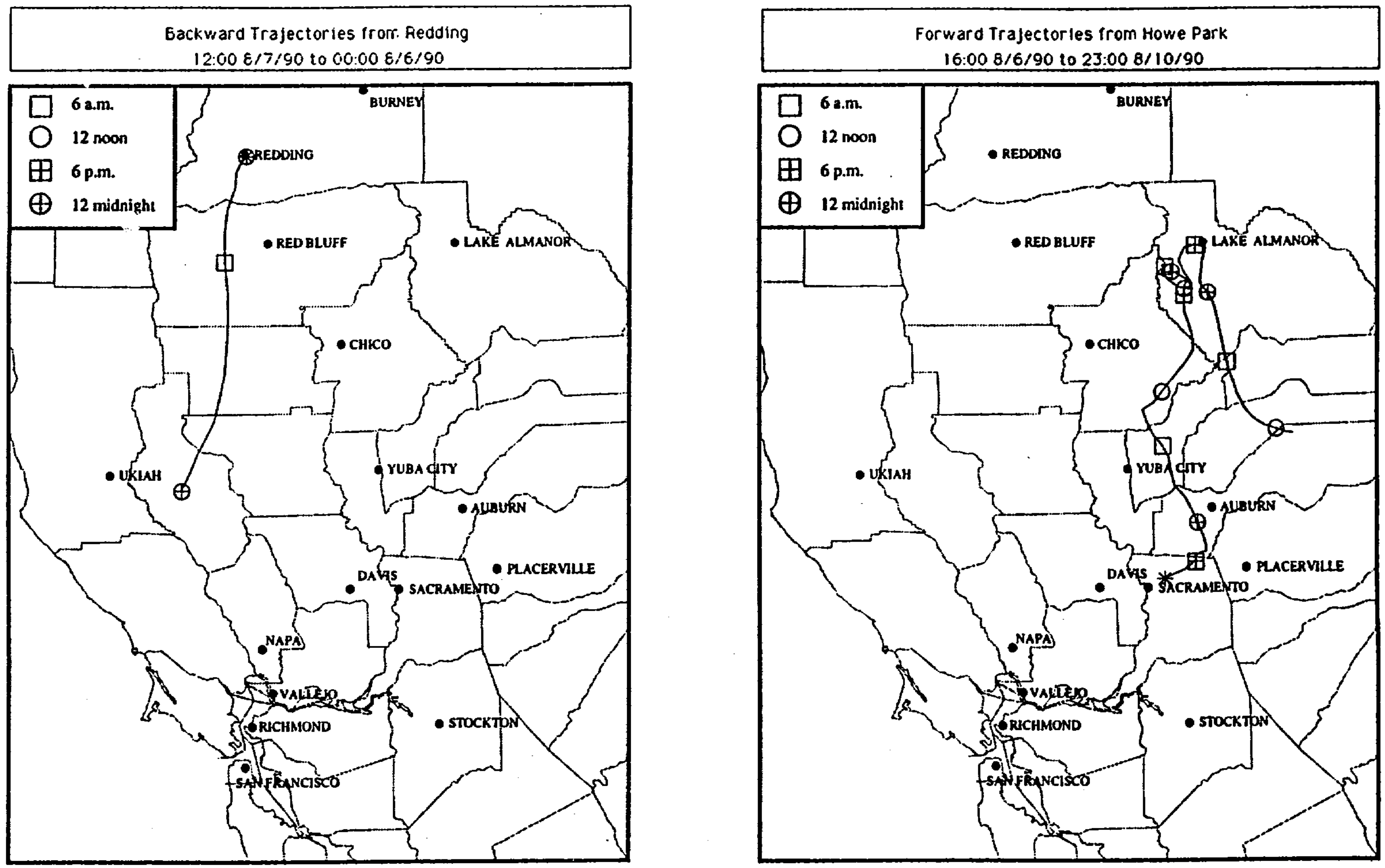


Figure 2-23. Aloft 400 m Back Trajectory From Redding on August 7, 1990 Beginning at 1200 PST, and 400 m Forward Trajectory From Howe Park on August 6, 1990 Beginning at 1600 PST.

before midnight. However, this forward trajectory crosses into the high plateau and foothills on the eastern side of the Sacramento Valley. The true trajectory probably lies somewhere in between. These trajectory results are probably an artifact of the data, since the aloft data are from sites at the northern edge of the Broader Sacramento area where the afternoon flow is from the southsouthwest. If we had 400 meter wind data from locations further north in the Sacramento Valley, we would probably find that the Redding aloft trajectory had arrived from the Lower Sacramento Valley.

The diurnal ozone concentrations for Chico on August 8, 1990 were shown in Figure 2-21. There are two ozone peaks, a very sharp one at 0700 PST and a broad peak at 1200-1400 PST. The surface back trajectories for Redding and Chico on this day are shown in Figure 2-24. Notice that there is a convergence zone in the Upper Sacramento Valley somewhere between Chico and Redding. The Chico trajectory indicates that the 1200-1400 PST ozone peak had arrived in the Chico area the previous evening about 1800 PST and had remained in the area. This arrival time is consistent with the ozone peak at about 1500-1600 PST on August 7. Figure 2-25 shows the 400 meter back trajectory for Chico. The aloft trajectory indicates a drainage flow out of the foothill area northeast of Chico in the morning. Although these winds are suspect because they are generated by data further south, they still show realistic timing and seem to match the conditions on this day. The early-morning ozone peak may be the result of re-circulation of material which left Chico on the previous day.

Flows were different on the 9th. Both the Chico surface and 400 meter back trajectories arrived from the northnorthwest; the trajectories indicate that the air parcels had been in the Redding area the previous afternoon and evening. However, this air mass could have been part of the air mass that arrived in the Upper Sacramento Valley on the afternoon of August 7 (see Chico back trajectory in Figure 2-24, for example). If this is the same air mass, then this episode is an example of transport into the Upper Sacramento Valley on August 7 and then emissions accumulation and continued reaction with little net transport for the next two days.

2.2.4 Comparison of Trajectory Results with Timing of the Peak Ozone Concentration

If a number of ozone monitoring sites lie along a suspected transport path, then the magnitude and timing of peak ozone concentrations can be evaluated. A consistent transport pattern exists if the ozone peaks occur later at each successive downwind site, and if the time between peak concentrations is consistent with the measured wind speeds (for example, see discussion in Section 4.3 of Roberts, et al., 1990). Note that this technique works best when there are few emissions sources along the transport path; otherwise allowances must be made for modifications to the diurnal ozone profiles by local emissions. In addition, this technique only works when the transport occurs at the surface, rather than aloft. This method does not work very well in the Upper Sacramento Valley, as illustrated below using ozone episodes from 1987. Additional discussion of this analysis method is presented in Section 4.2 using data from the North Central Coast.

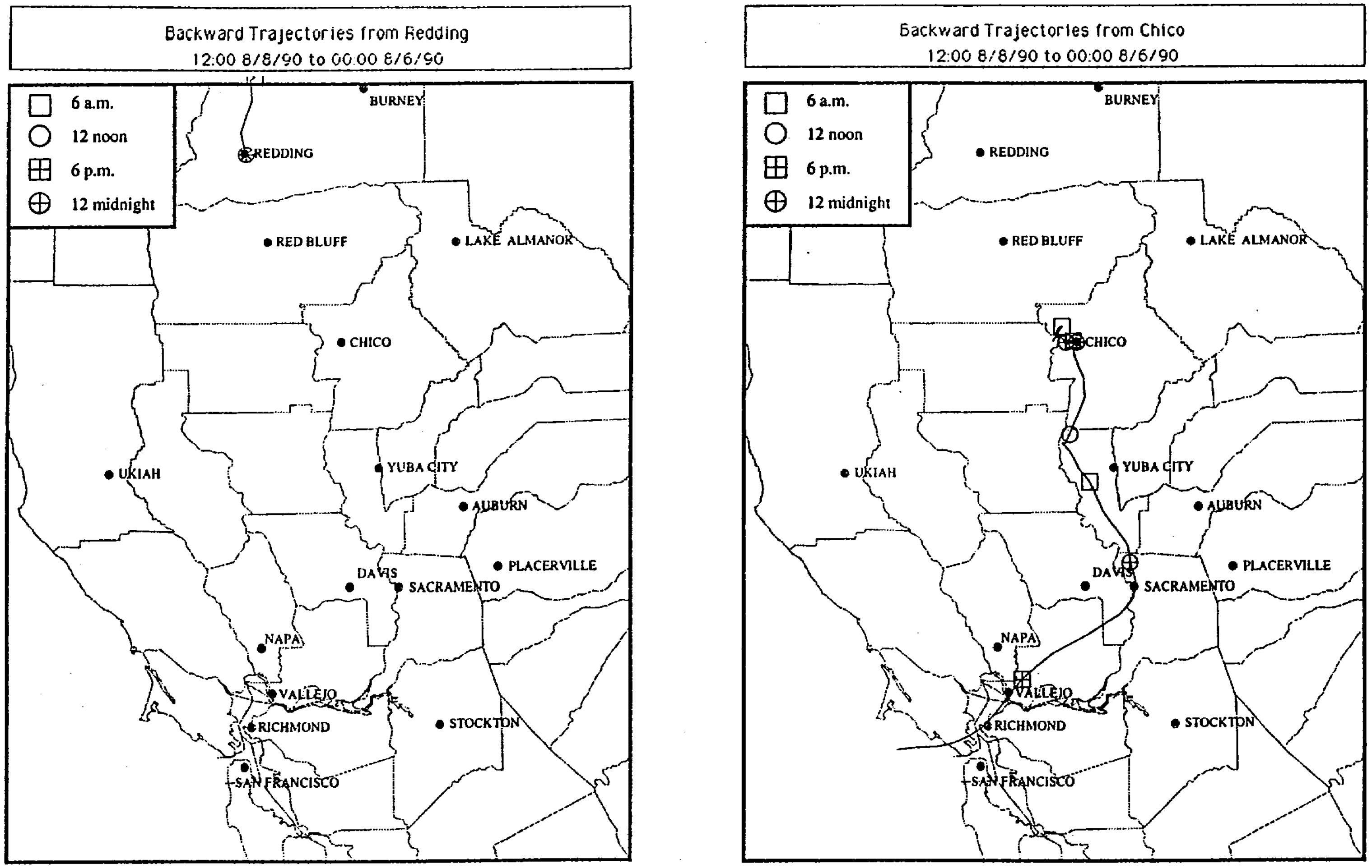


Figure 2-24. Surface Back Trajectories From Redding and Chico on August 8, 1990 Beginning at 1200 PST.

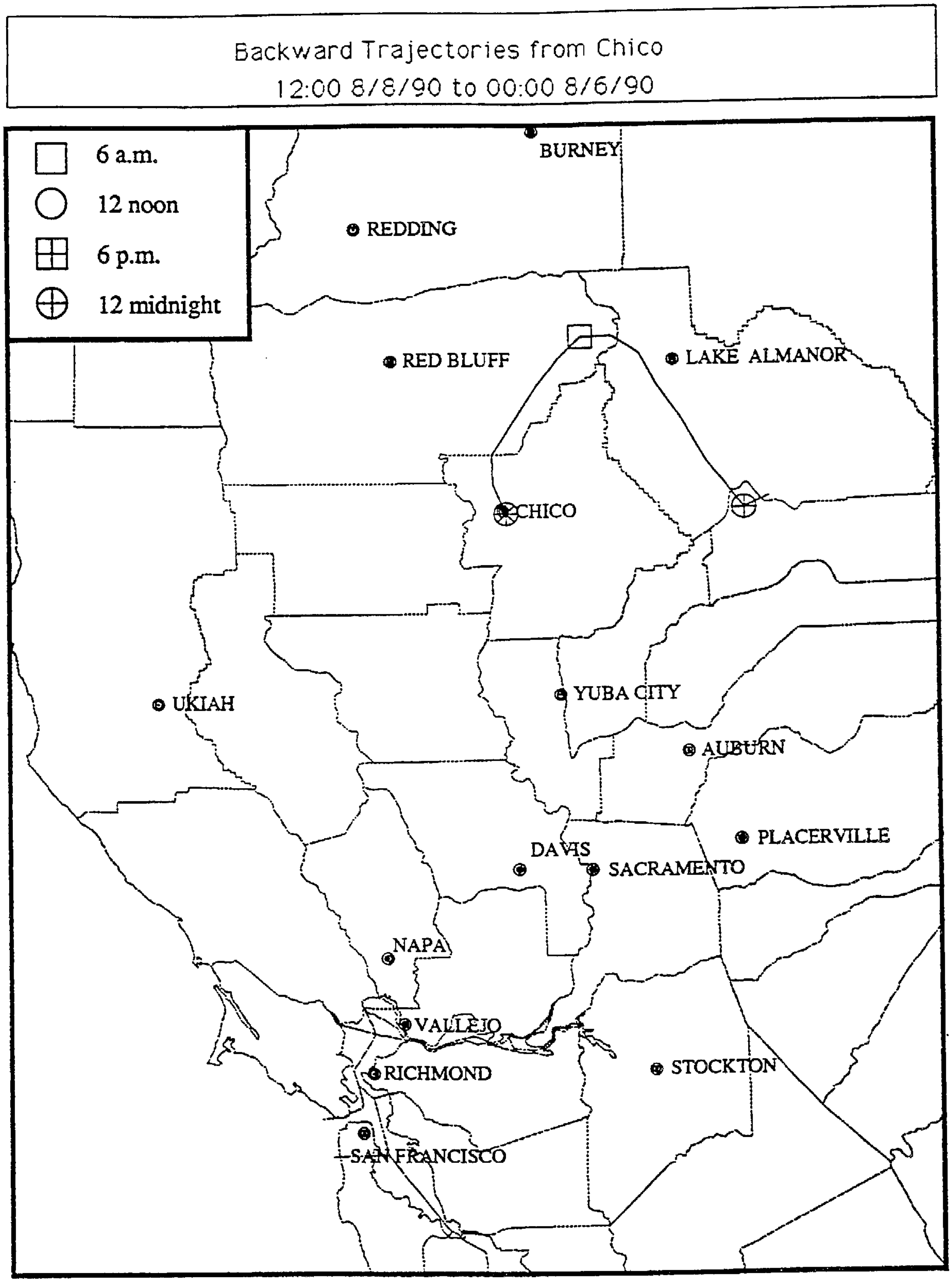


Figure 2-25. Aloft 400 m Back Trajectories From Chico on August 8, 1990 Beginning at 1200 PST.

The estimated trajectories for July 14, 1987 (see Figure 2-14) indicated slow transport up the valley to Chico and Red Bluff, with carryover plus transport on the previous day contributing to ozone concentrations at Redding. The peak ozone concentration and time of the peak for Upper Sacramento Valley monitoring sites on this day are given below:

Site	Ozone Max (pphm)	Time of Max (PST)
Arbuckle	10	1300-1600
Colusa	10	1600
Willows	8	1100-1800
Anderson	11	1100
Redding	11	1000-1100
Pleasant Grove	10	1300
Yuba City	9	1300-1600
Chico	9	1300, 1700-1800

The peak ozone concentration progresses up the west side of the valley from Arbuckle to Colusa and possibly to Willows, and up the east side of the valley from Pleasant Grove to Yuba City to Chico (the second peak), but the timing requires much faster wind speeds than the trajectories indicate. The progression breaks down at Anderson and Redding; these peaks occur too early for same-day transport.

On June 3, 1987 and June 26, 1987, the ozone peak progresses up both sides of the valley, but the timing again requires high wind speeds. However, back trajectories for Redding, Red Bluff, and Chico on these days indicate no transport. Thus, the results of this method do not agree with surface transport times and do not distinguish between transport and non-transport days. Poor performance might be caused by faster transport aloft or complicated by continuing ozone formation all along a transport path (see discussion in Section 4.2).

2.3 OZONE FLUX ESTIMATES

We prepared some simple pollutant flux plots in order to better understand when transport occurred and how much ozone and NO_x were being transported. We calculated a simple relative pollutant flux by multiplying the hourly pollutant concentration by the hourly wind speed in the transport direction. Figure 2-26 shows the relative ozone flux at the Sutter Buttes monitoring site during the June 15 to September 15, 1990 period. Each point on the plot represents one hour during that period. The points are randomly offset within the exact hour in order to allow similar flux values at the same hour to be distinguished. The flux plane has been oriented along an east-west line through the monitoring site; this is perpendicular to the mean wind direction. Thus we used the resultant wind speed parallel to 180 degrees in our calculation of the ozone flux.

The Sutter Buttes site is located near the peak of the Buttes at an elevation of about 650 meters msl with the Sacramento Valley floor at about

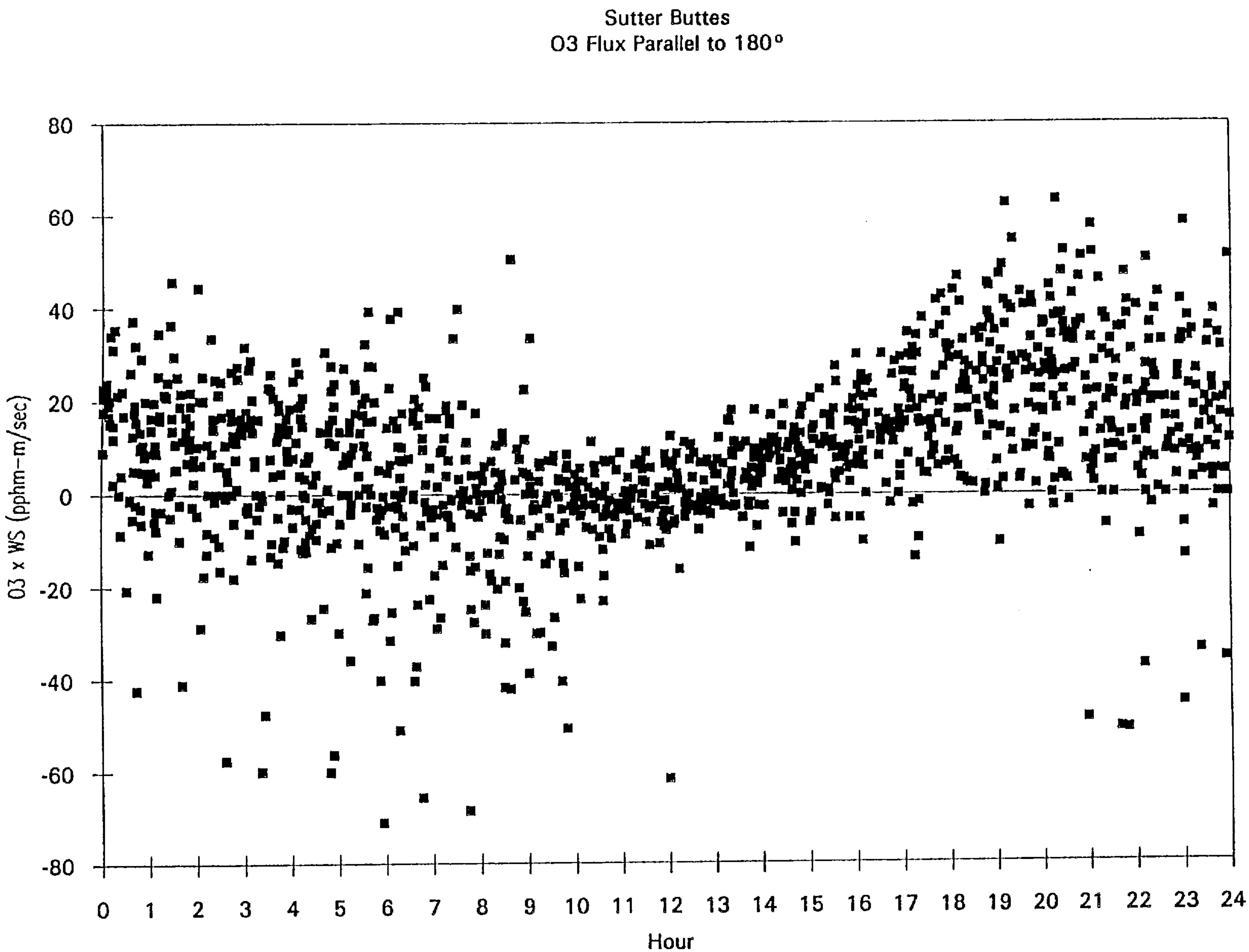


Figure 2-26. Estimated Relative Ozone Flux at Sutter Buttes, June 15 through September 15, 1990.

STBO3HR.XLC

9/20/91 12:35 PM

15 meters msl. The Buttes are like an isolated spire in the middle of the valley. Thus the ozone concentrations measured there represent aloft air, generally near the top of the mixed layer during the day and in an aloft layer well above the nocturnal boundary layer at night.

The y-axis of Figure 2-26 shows both positive and negative values for the ozone flux. This is a result of both southerly and northerly flow occurring at this site. The negative values occur during the night and early morning when northerly flow in the Sacramento Valley reaches this far south. In general, the highest relative ozone flux at the Sutter Buttes site occurs during the late afternoon and evening, from about 1800 PDT until about 0600 PDT. Low relative ozone flux occurs during the mid-day when wind speeds are low (about 20 percent of the time). Southerly flow produces pollutant transport into the Upper Sacramento Valley for about 60 percent of the hours during the June 15 to September 15, 1990 period. Similar results were obtained with the summer 1989 data from Sutter Buttes.

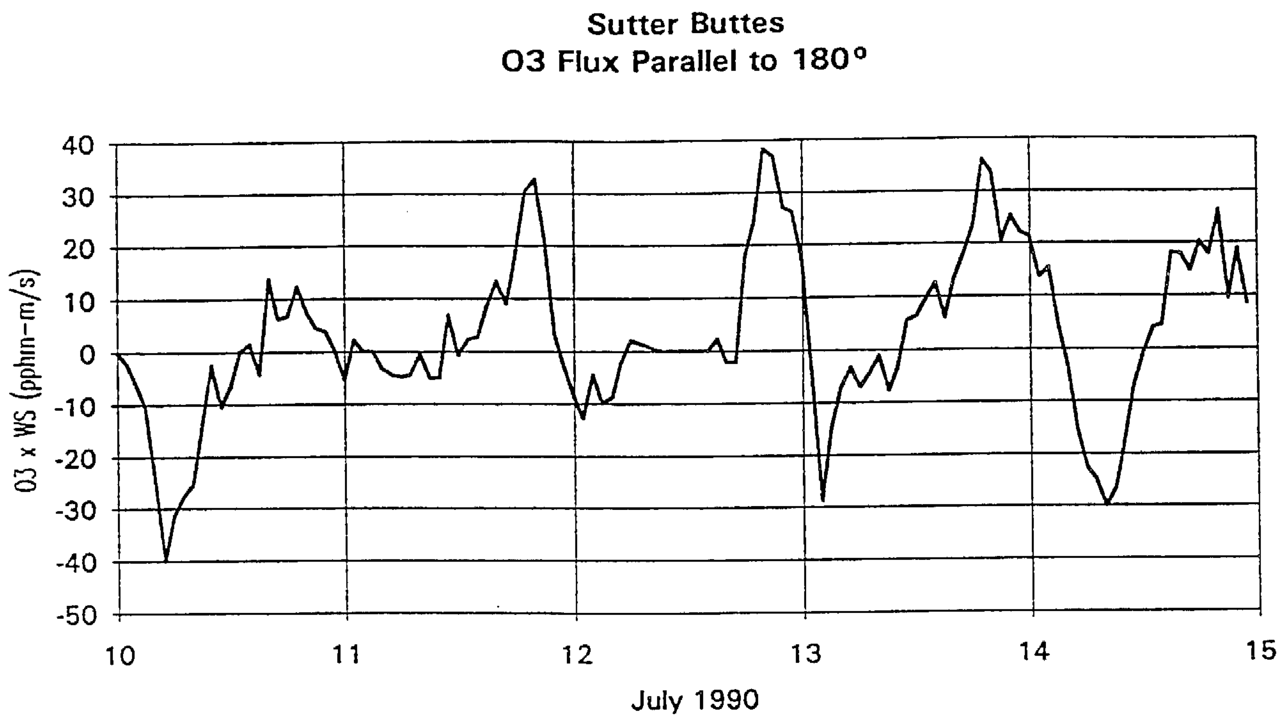
Figure 2-27 through 2-29 show the relative ozone flux, ozone concentration, and resultant wind speed for three periods in July and August, 1990. On most days, the higher flux during the late afternoon and evening is mainly caused by higher winds during that period than during other periods. Higher ozone concentrations on some days (for example, July 14th) can also contribute significantly. Notice that the northerly wind occurred almost every night during these periods, except during the night of August 10. The highest relative ozone fluxes were measured on August 2, 3, and 4. Also note that the ozone concentration at this aloft monitoring site is seldom below about 5 pphm. Similar results were obtained with the summer 1989 data from Sutter Buttes.

2.4 PRECURSOR CONTRIBUTION ESTIMATES

This section is divided into three parts. The first two summarize the general methods that were used to generate precursor emissions inventories for California and to estimate the relative precursor contributions to air parcels arriving at receptor sites in the Upper Sacramento Valley. We also used these methods for other receptor areas. The third section summarizes the results of our precursor contribution estimates for the Upper Sacramento Valley and discusses those results. The purpose of these analyses is to identify the contributions of transported precursors to ozone violations in the Upper Sacramento Valley as either inconsequential, significant, or overwhelming, relative to locally-emitted precursors. As ozone precursors, we are concerned with nitrogen oxides (NO_x) and reactive organic gases (ROG).

2.4.1 Summary of Emissions Inventory Methods

A gridded ROG and NO_x emissions inventory was prepared for all of California. Emissions were gridded separately for area sources, biogenic sources, on-road motor vehicles, and point sources. This inventory was prepared from the 1985 National Acid Precipitation Assessment Program (NAPAP) inventory for the state in the following manner:



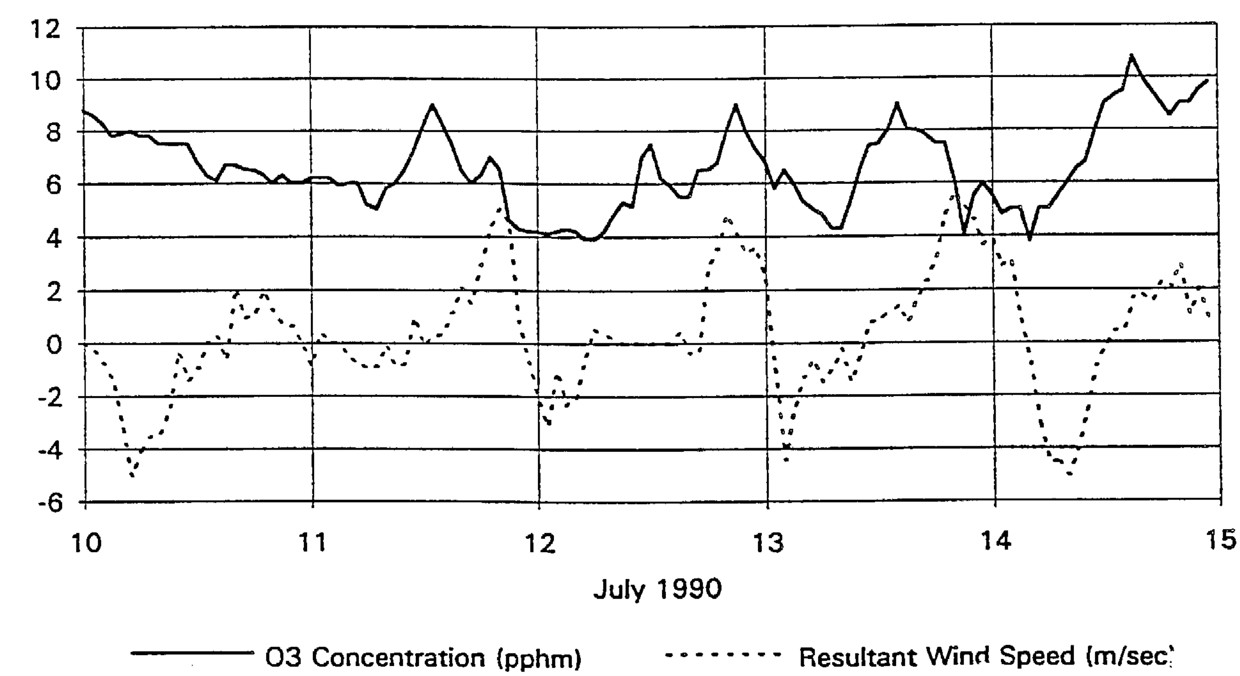


Figure 2-27. Estimated Relative Ozone Flux, Ozone Concentration, and Resultant Wind Speed at Sutter Buttes, July 10-14, 1990.

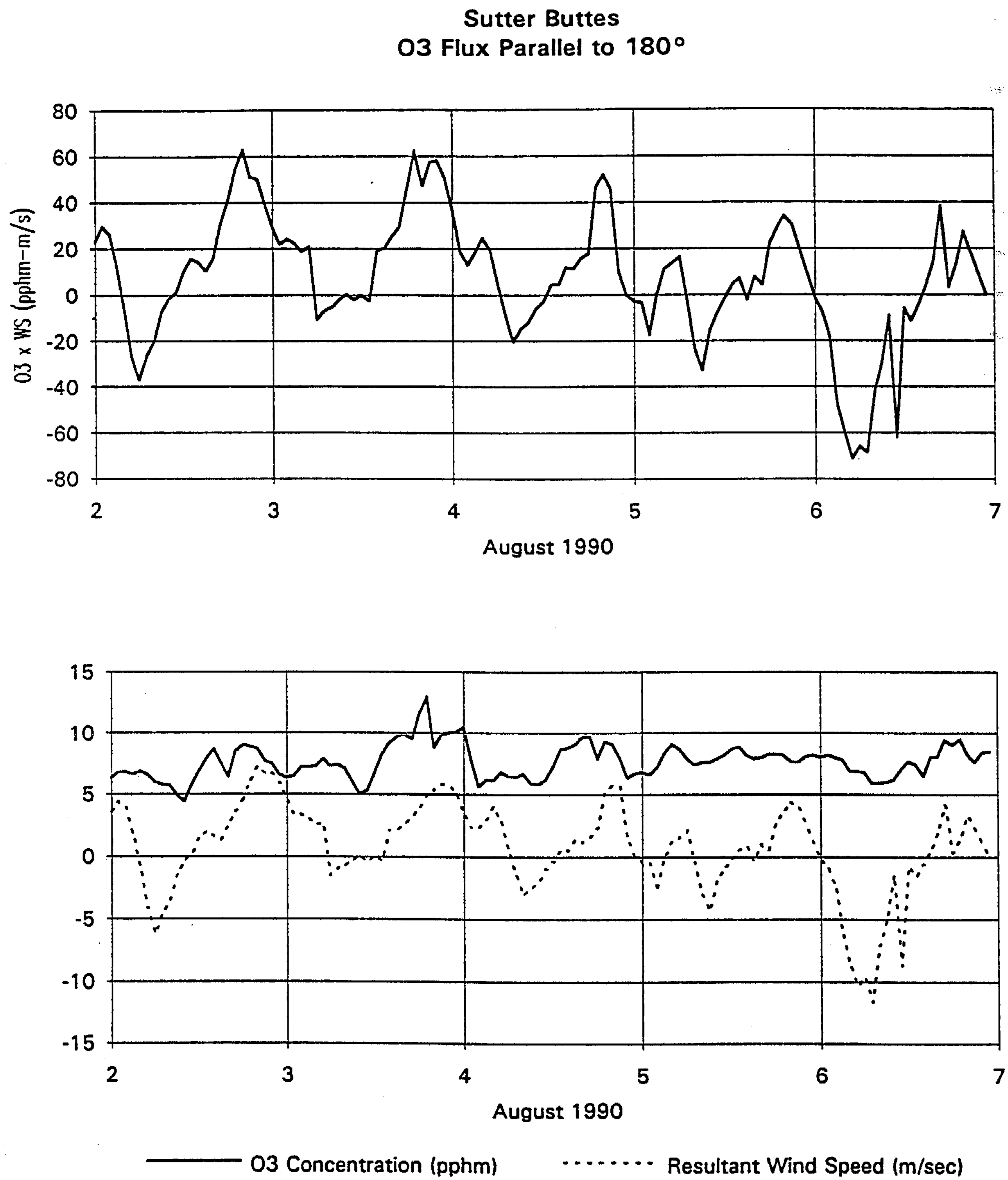


Figure 2-28. Estimated Relative Ozone Flux, Ozone Concentration, and Resultant Wind Speed at Sutter Buttes, August 2-6, 1990.

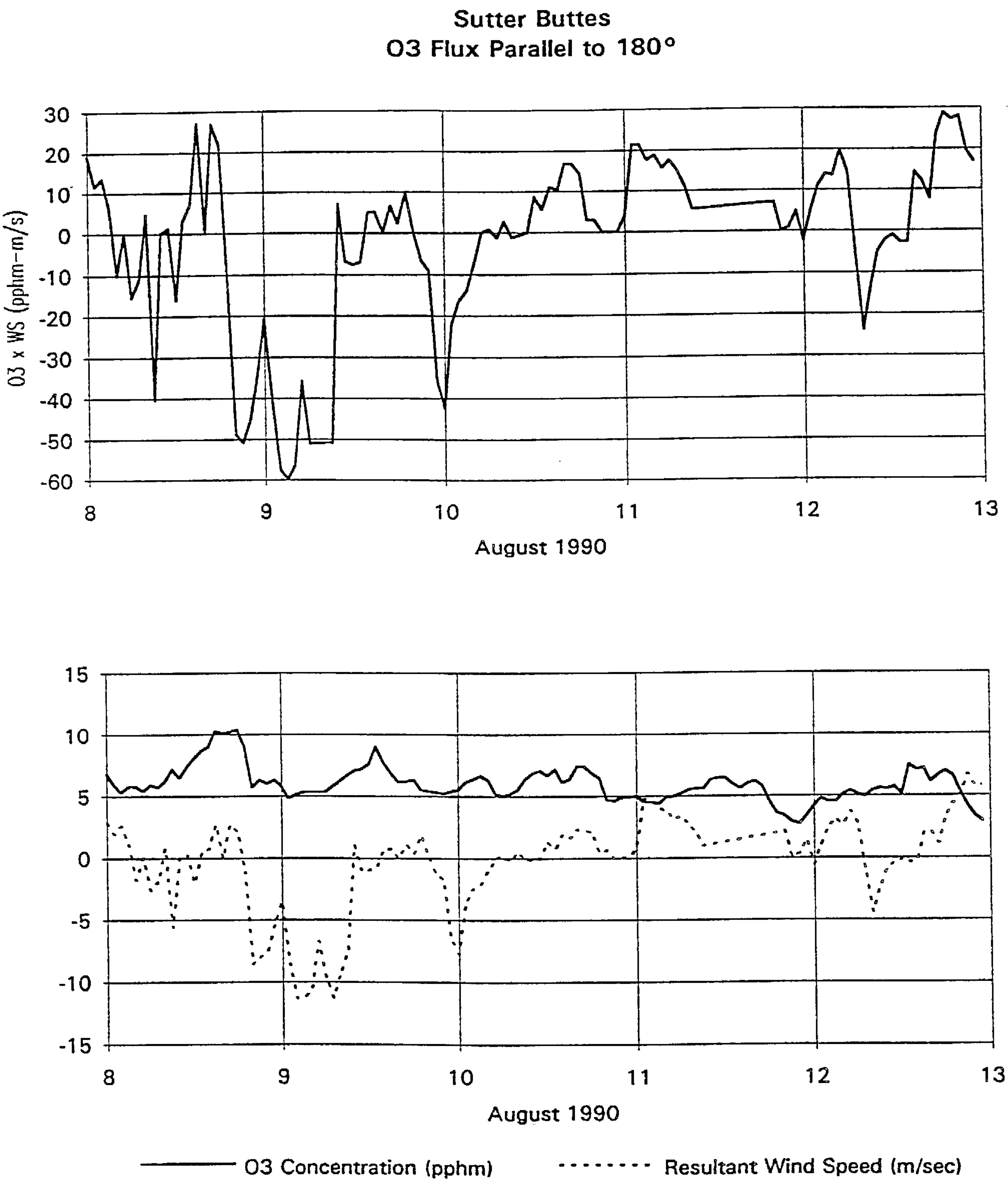


Figure 2-29. Estimated Relative Ozone Flux, Ozone Concentration, and Resultant Wind Speed at Sutter Buttes, August 8-12, 1990.

Point Sources: Emissions were spatially allocated to grid cells based on the location data provided in the NAPAP inventory. Temporal adjustment from annual average emissions to summer weekday emissions was accomplished using the operating information for each point. Missing temporal allocation data were replaced with default parameters (24 hours per day, 7 days per week, 52 weeks per year operation). THC emissions were converted to ROG emissions (reported in CH_4 weight equivalents) using standard EPA volatile organic compounds (VOC) speciation profiles by process.

Area Sources: Emissions were spatially allocated to grid cells using a variety of spatial surrogate indicators, including population, county area, and the following land-use categories: urban, agricultural, rural, range, and water. To temporally adjust emissions from annual average to summer weekday levels, ARB default temporal profiles by source category were used by pairing ARB source categories with NAPAP source categories. THC emissions were converted to ROG emissions using standard EPA VOC speciation profiles by process.

On-Road Motor Vehicles: Emissions from on-road motor vehicles were adjusted from the annual average emissions provided in NAPAP by applying the ratio of MOBILE4 emission factors calculated at typical July temperatures and summer Reid vapor pressure (RVP) to emission factors calculated at the average temperatures and RVPs used to generate the NAPAP inventory. At this point, composite emissions were also disaggregated into exhaust, evaporative, refueling, and running loss components. This was done separately for seven climatological regions of California: the north coast, the northeast interior basin, the Sacramento Valley, the San Joaquin Valley, the central coast, the south coast, and the southeast desert basin. Additional seasonal adjustments based on standard vehicle miles traveled (VMT) and monthly variations from ARB were also applied. Emissions were then spatially allocated according to a combination of population, urban, and rural land-use surrogates. THC emissions were converted to ROG emissions using standard EPA VOC speciation profiles for exhaust and evaporative mobile source emissions by vehicle type.

Biogenic Emissions: Summer biogenic emissions of isoprene, a-pinene, and other nonmethane hydrocarbons were obtained at the county level from the Washington State University national biogenic inventory and spatially allocated using land-use surrogates. Temporal allocation of emissions by hour was accomplished using representative diurnal temperature and light intensity curves. Emissions were converted to Carbon Bond 4 species and reaggreated as ROG to provide a compatible format with the anthropogenic inventory components described above. There are no NO_x emissions from this source.

The attached emissions density plots (Figures 2-30 through 2-36) show the spatial distribution of daily total emissions for each of the four source types described above. Please note the different scales on these plots.

Within the funding available for this study, we were not able to provide any quality assurance or uncertainty analyses of the emissions data used in the gridding process. We used default parameters for all missing data such as temporal allocation factors.

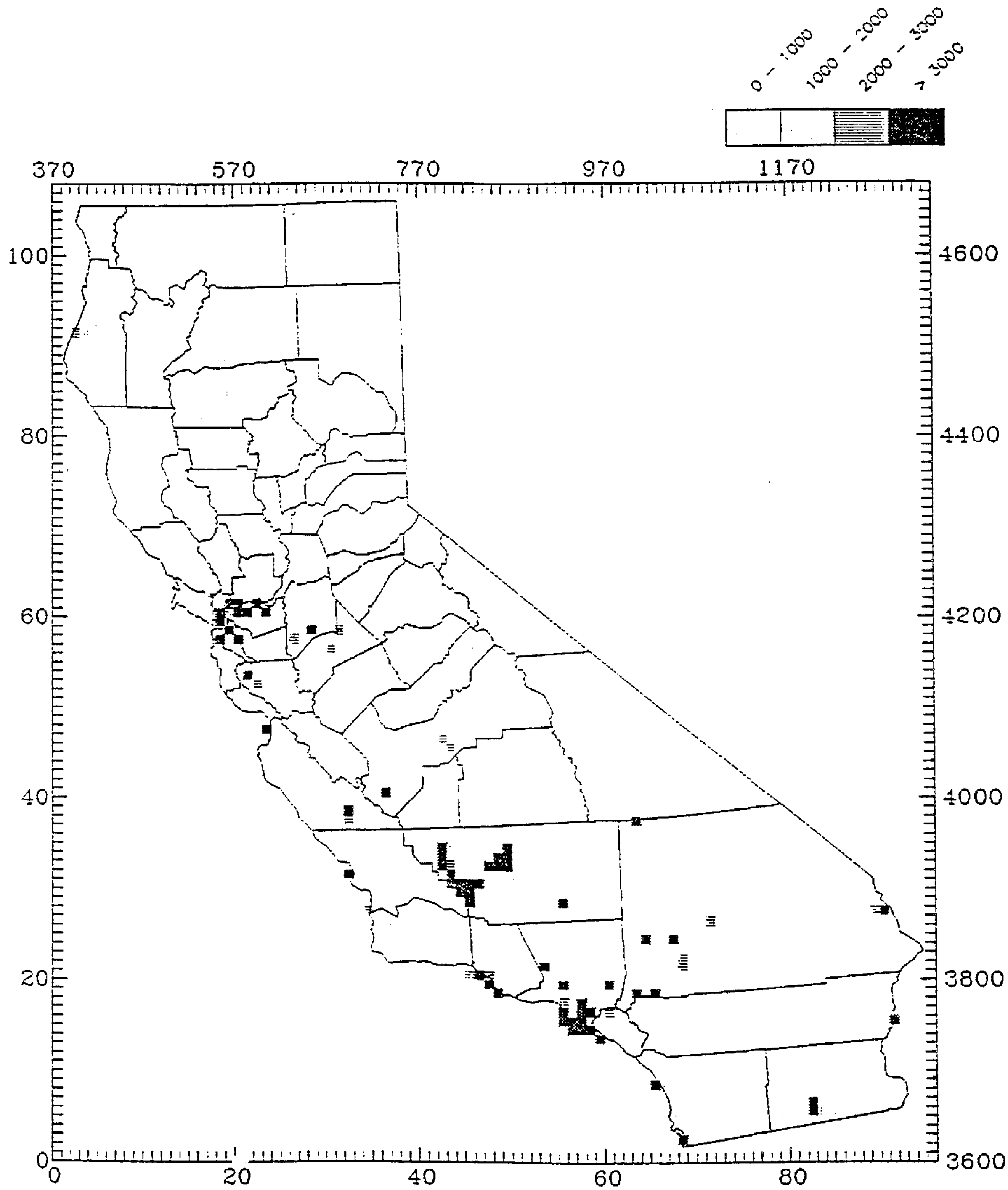


Figure 2-30. 1985 California NO_x Point Source Emissions (July weekday).
Total: 733,239 kg/day

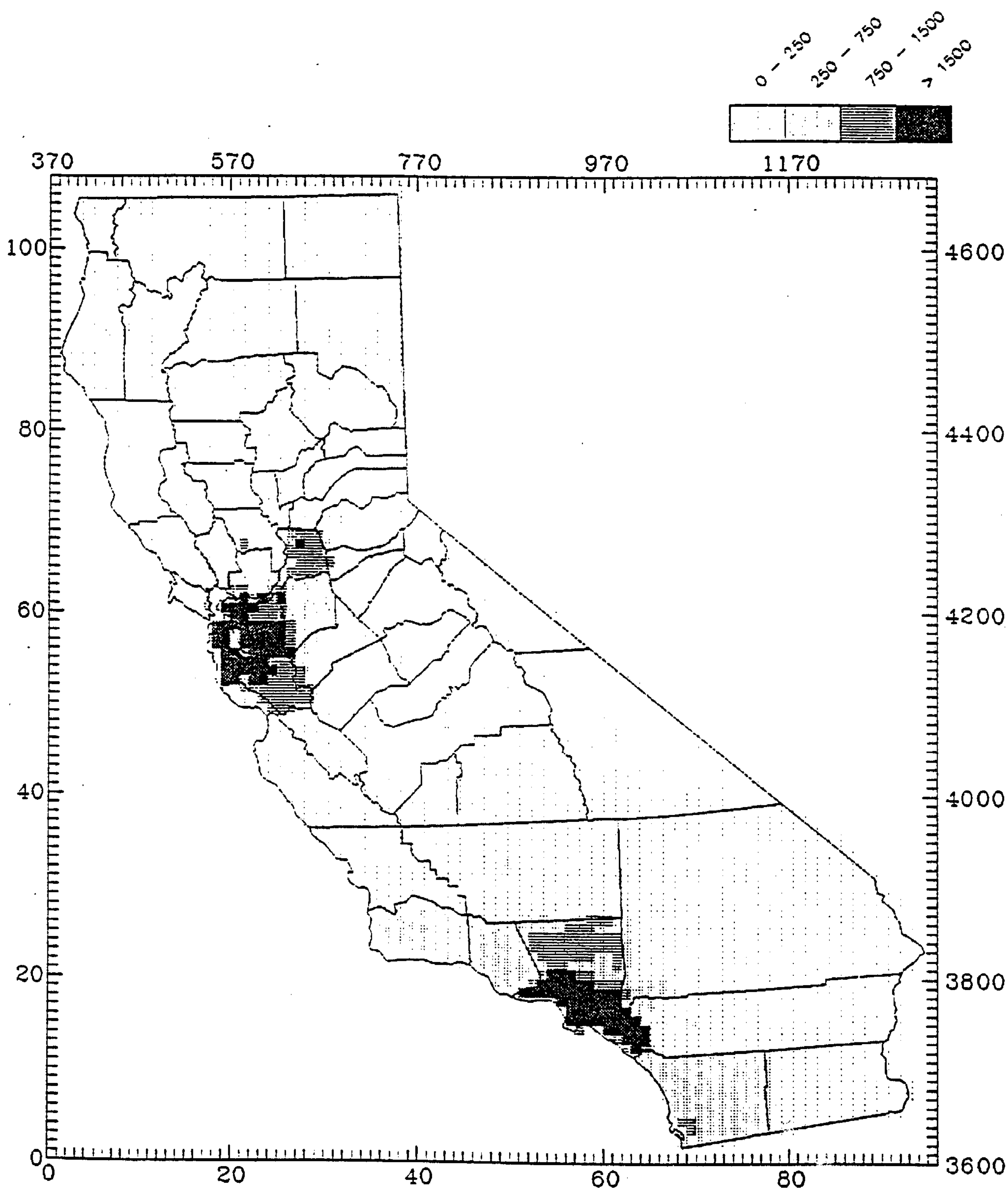


Figure 2-31. 1985 California NO_x Area Source Emissions (July weekday). Total: 813,861 kg/day

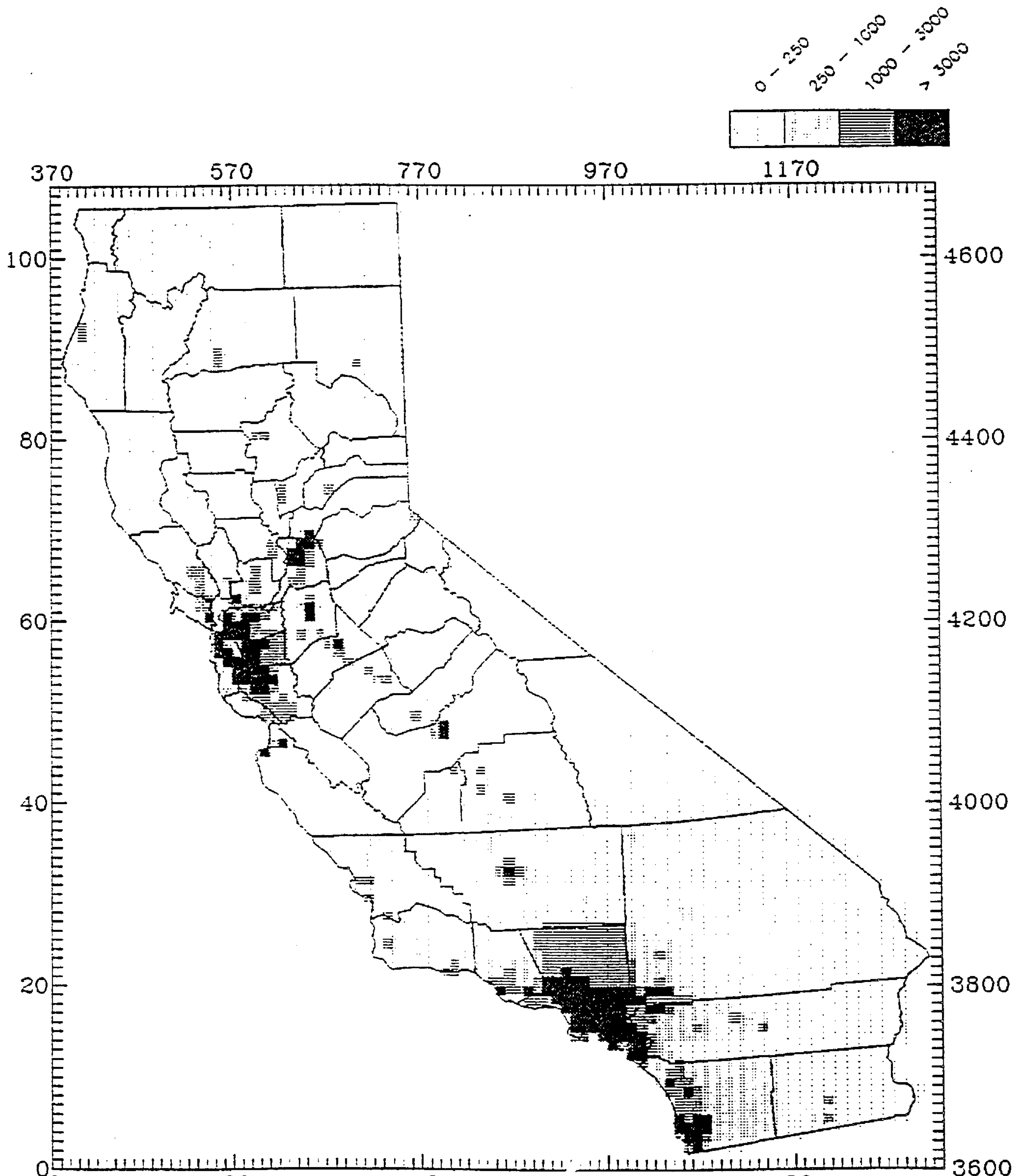


Figure 2-32. 1985 California NO_x Motor Vehicle Emissions (July weekday). Total: 1,794,833 kg/day

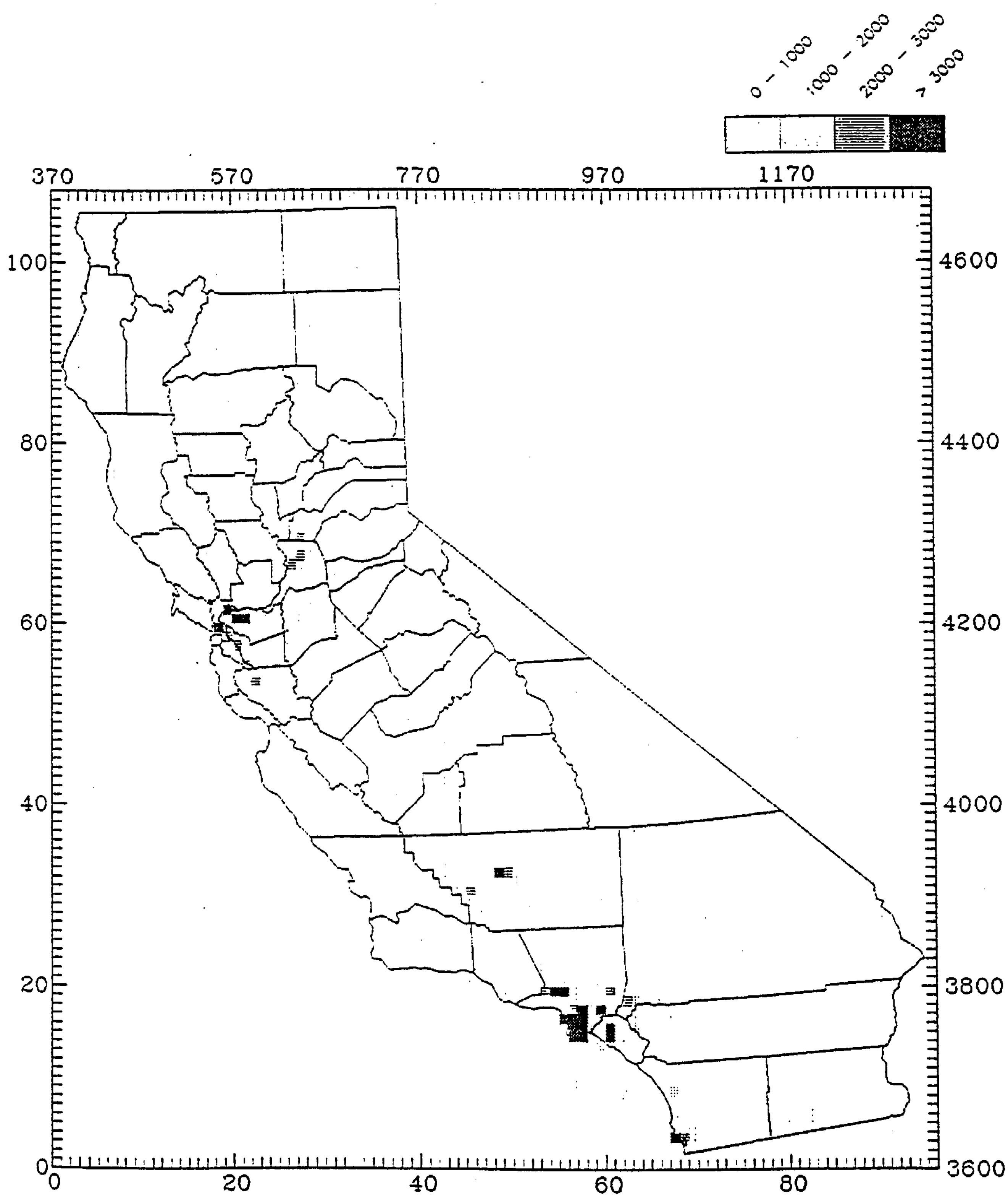


Figure 2-33. 1985 California ROG Point Source Emissions (July weekday).
Total: 214,664 kg/day

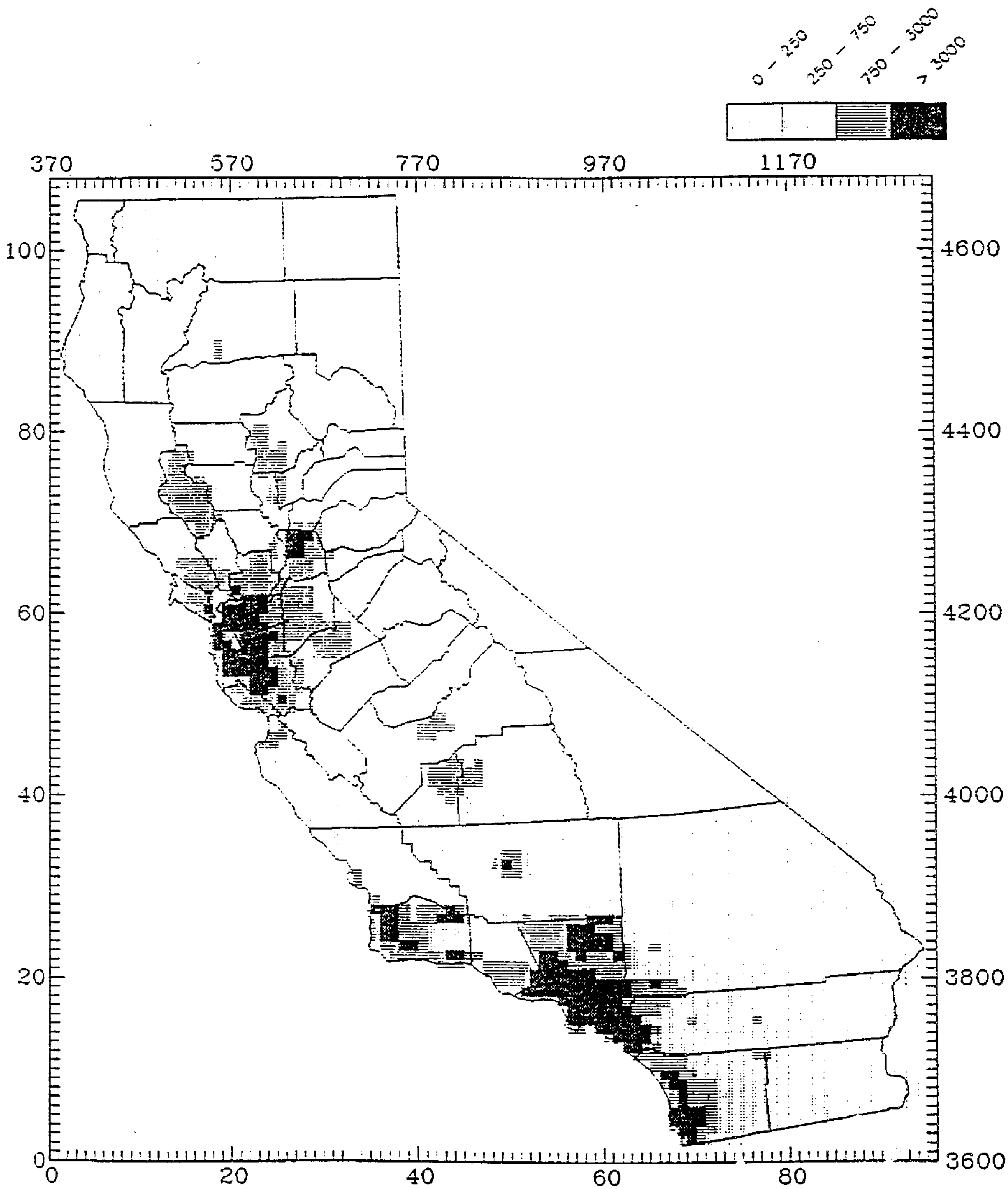


Figure 2-34. 1985 California ROG Area Source Emissions (July weekday). Total: 2,823,393 kg/day

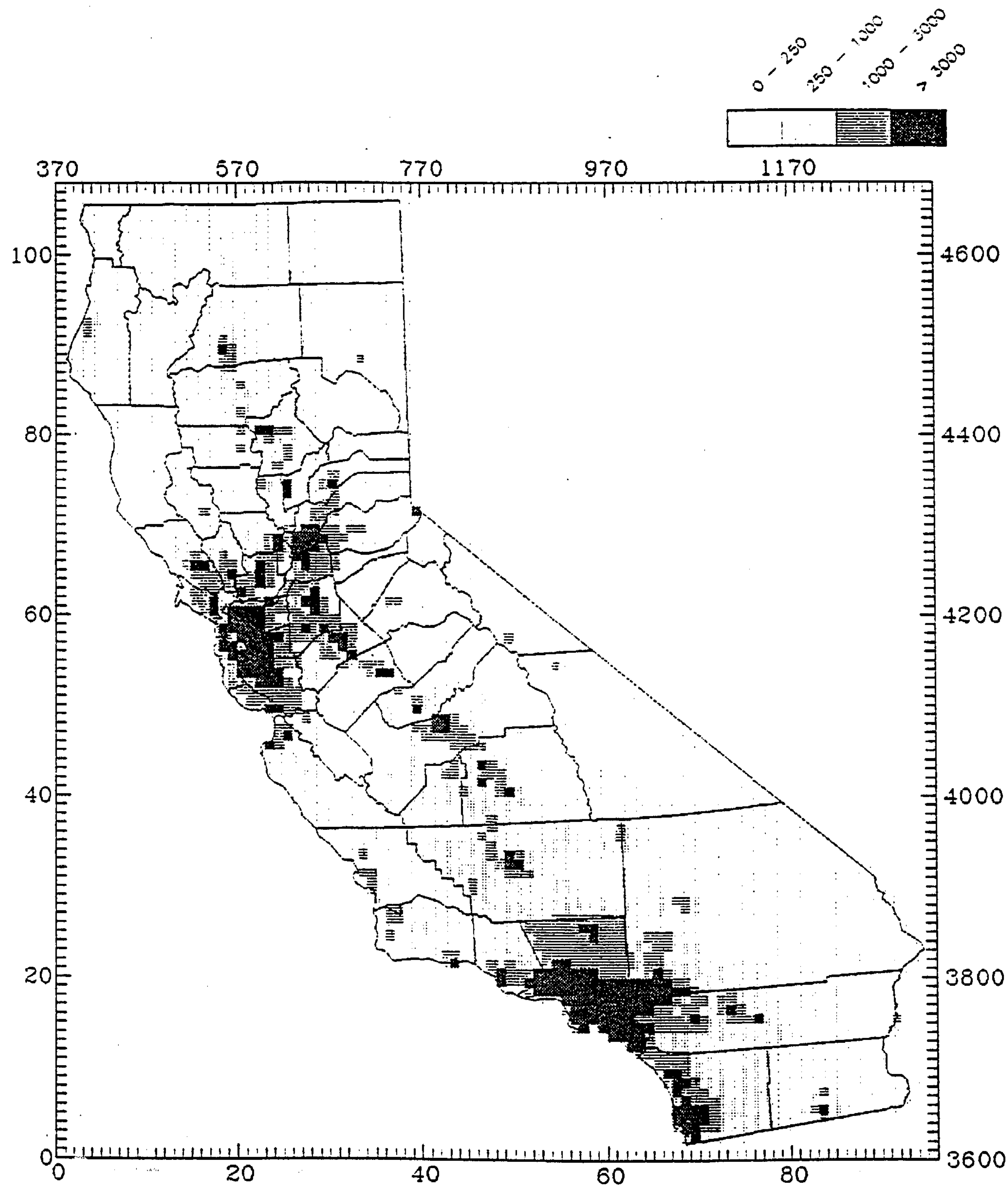


Figure 2-35. 1985 California ROG Motor Vehicle Emissions (July weekday).
Total: 3,224,918 kg/day

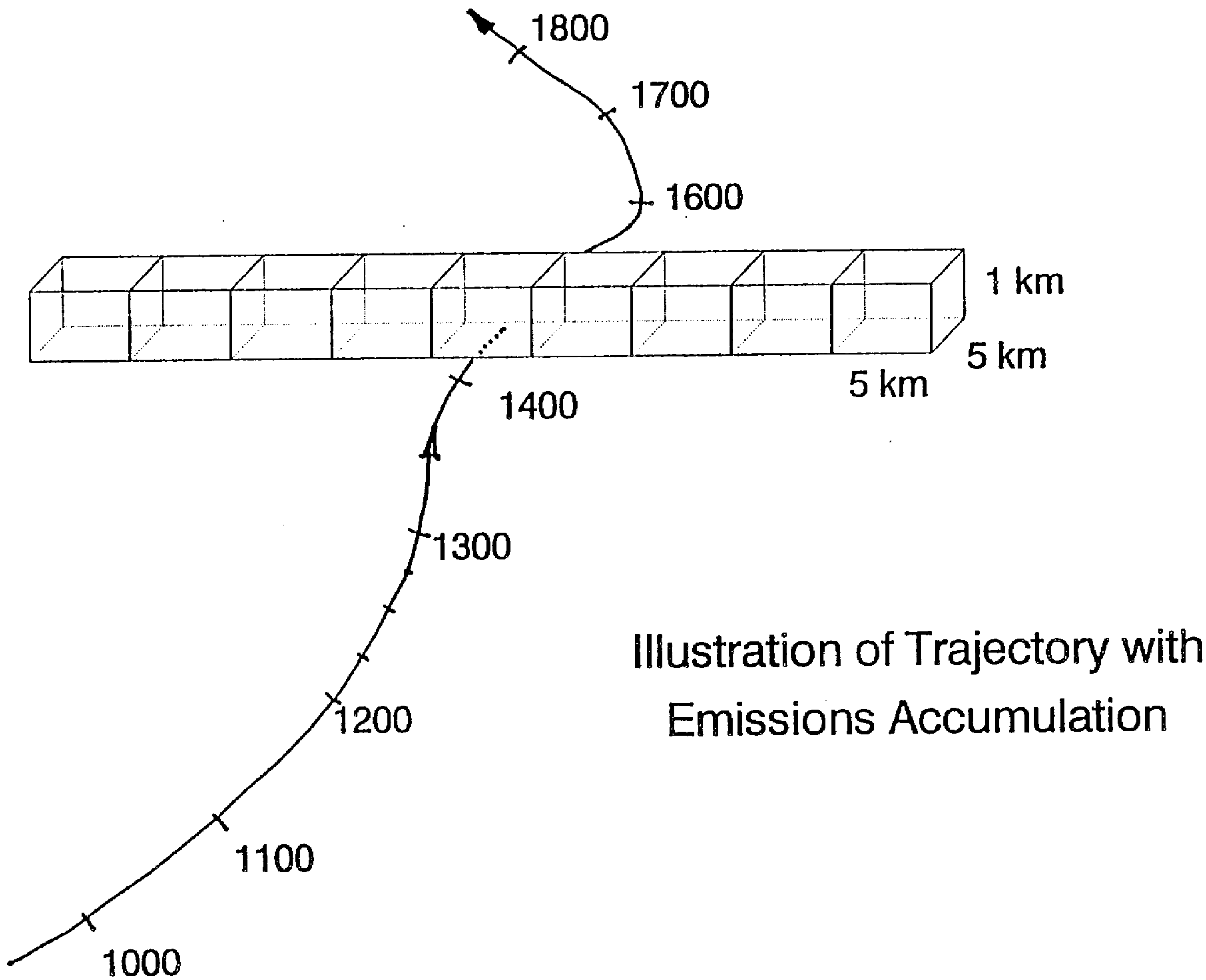


Figure 2-37. Illustration of Precursor Accumulation Geometry Along a Trajectory Path.

although we assumed the 45 km wide box to be 1 km deep and 1 km high, this assumption did not affect the relative emissions contributions.

- Accumulated NO_x and ROG emissions in each of nine cells during each 30-minute time step. The accumulated emissions for a given cell were the hourly emissions for the grid located under the center of the cell, divided by two to match the 30-minute time step. Emissions for each source area were accumulated separately. To allow for emissions from four different source areas, this required accounting for eight species, four species each for NO_x and ROG, in each of the nine cells.

- Accumulated emissions along the trajectory for two cases, one with no reaction or loss of the emissions and a second with a first-order loss rate for NO_x and for ROG. The rates we used were:

Species	Day (%/hr)	Night (%/hr)
NO_x	15	5
ROG	3	0

  The rates were selected to represent the typical net loss of precursor by reaction and deposition in an urban photochemical system. This is obviously a simplified assumption, but one which is more realistic than no net loss. The purpose of including a net loss rate was to evaluate how the relative contributions of upwind and downwind areas changed when reaction was added.

- At the end of the trajectory, we averaged the accumulated emissions for all nine cells together and reported the relative contributions of the four source areas for NO_x and for ROG.

Figure 2-38 shows the relative concentrations of accumulated ROG from different source regions along an example surface trajectory without reaction. The trajectory for this example was shown in Figure 2-18. As the trajectory passes over the Bay Area, the ROG accumulates and eventually remains constant after the trajectory passes into the Broader Sacramento area. Note that there is some accumulation in both source areas while the trajectory is near the boundary between two adjacent areas; this is caused by the wide box. Notice that without reaction, the relative contribution of the three source areas is about equal for this trajectory. This illustrate how the biogenic emissions for the Upper Sacramento Valley cause a significant contribution to the accumulated ROG for a Chico back trajectory.

When reactions are included, the relative contribution of the Bay Area and Sacramento emissions drop significantly (see Figure 2-39). Because this surface trajectory was quite slow, the accumulated emissions from early along the trajectory path have been reduced significantly by reaction. Notice that there were no losses at night when we have specified the ROG reaction rate to be zero. Now that reaction has been included, the relative contribution of the Upper Sacramento Valley is much higher than for the case without reaction.

Figures 2-40 and 2-41 illustrates the relative influence of using aloft versus surface trajectories for the relative ROG and NO_x precursor

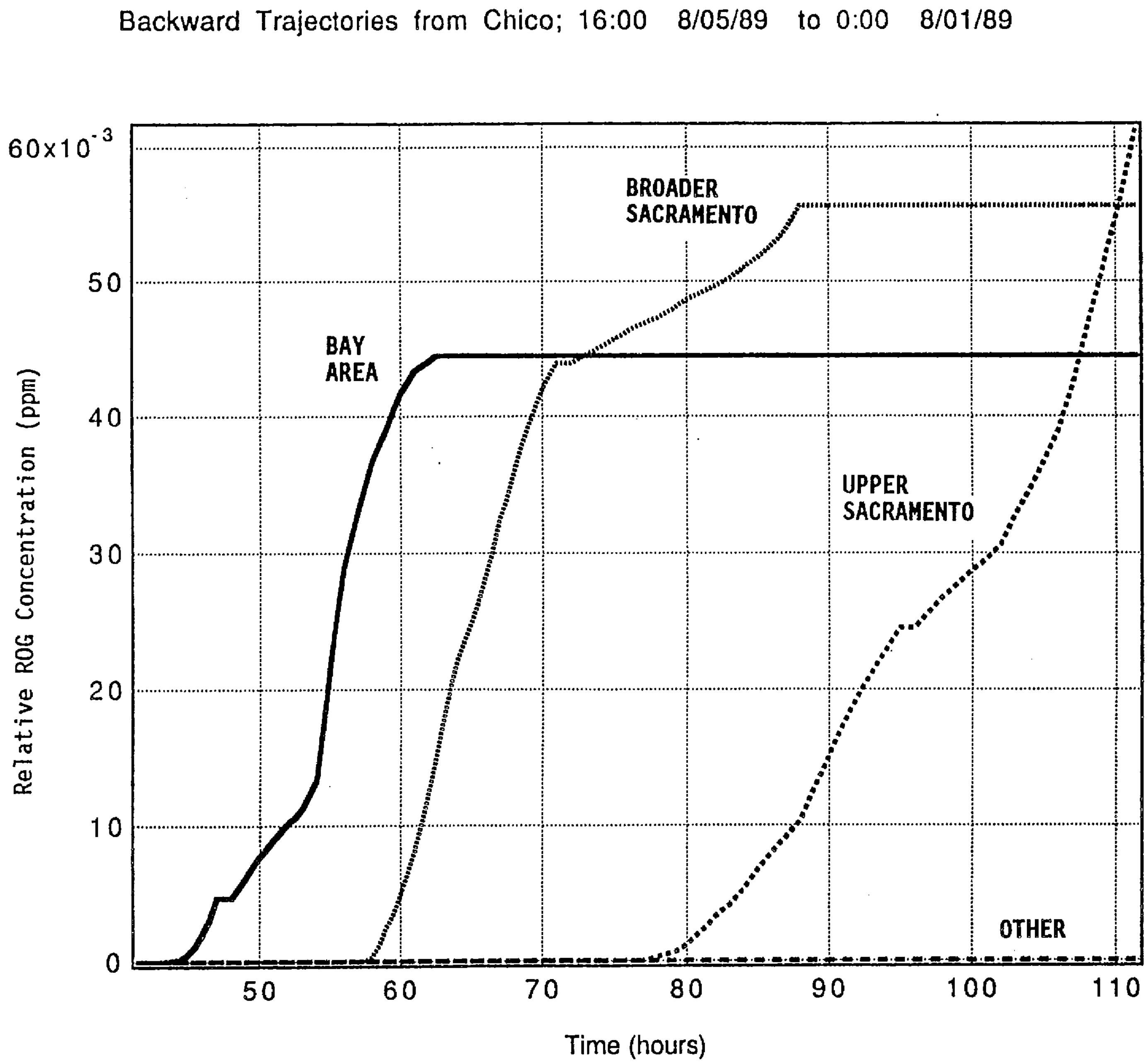


Figure 2-38. Example of ROG Accumulation Along a Surface Trajectory Path Without Reaction.

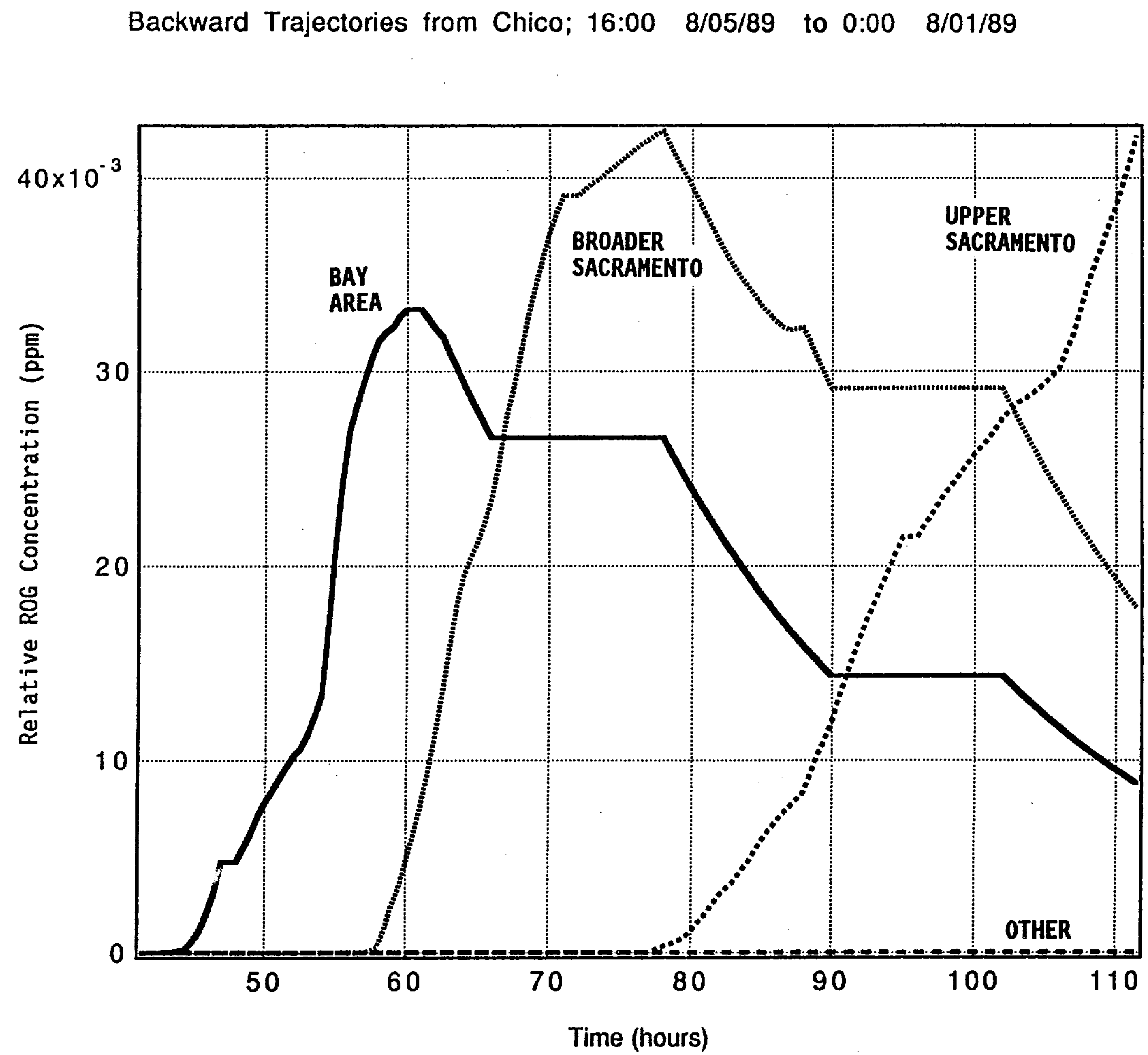


Figure 2-39. Example of ROG Accumulation Along a Surface Trajectory Path With Reaction.

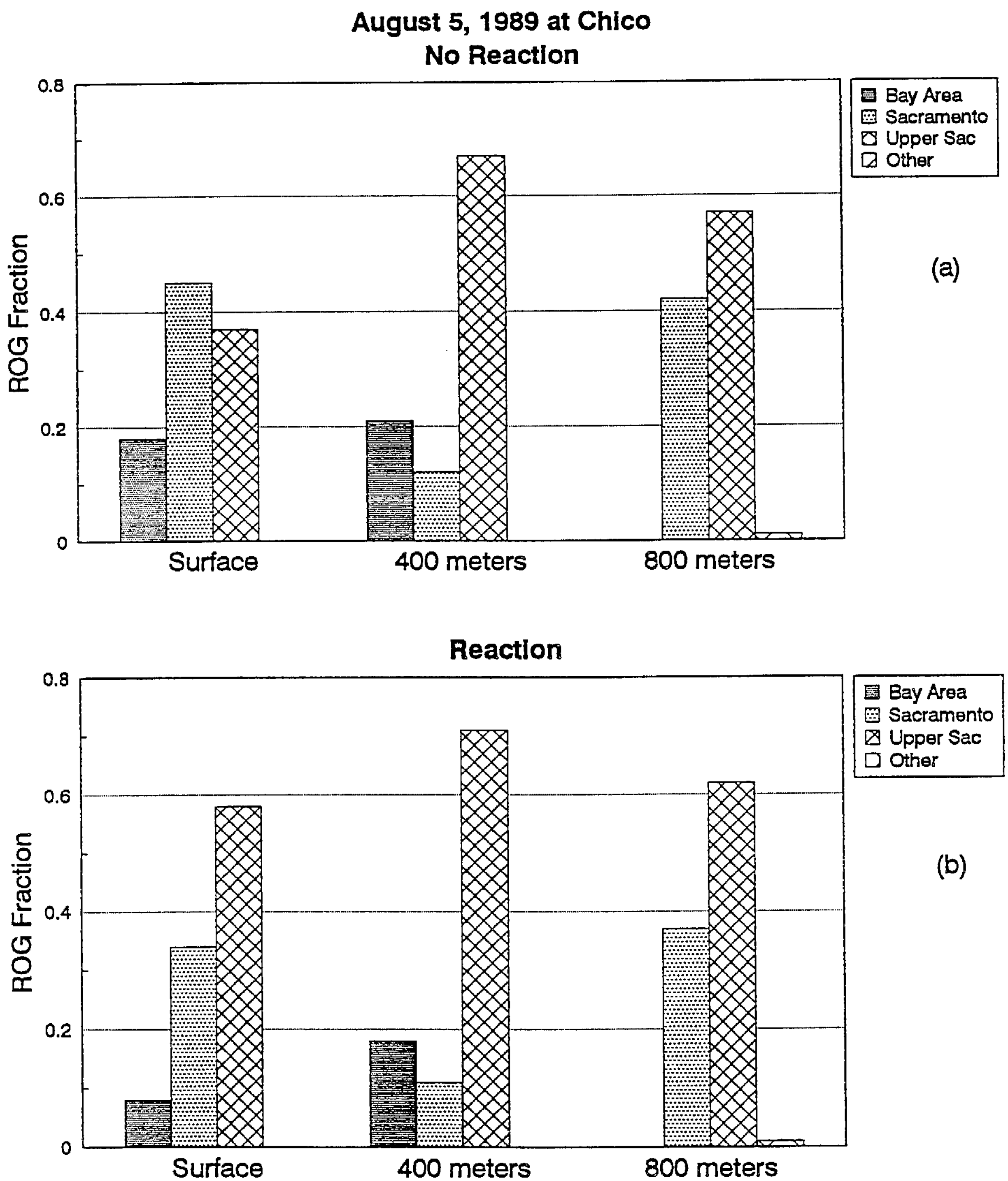


Figure 2-40. ROG Emissions Contribution Estimates Without Reaction (a) and With Reaction (b) for Surface, 400 Meter, and 800 Meter Back Trajectories From Chico on August 5, 1990 (Average of Three Trajectories at 1200, 1400, and 1600 PST).

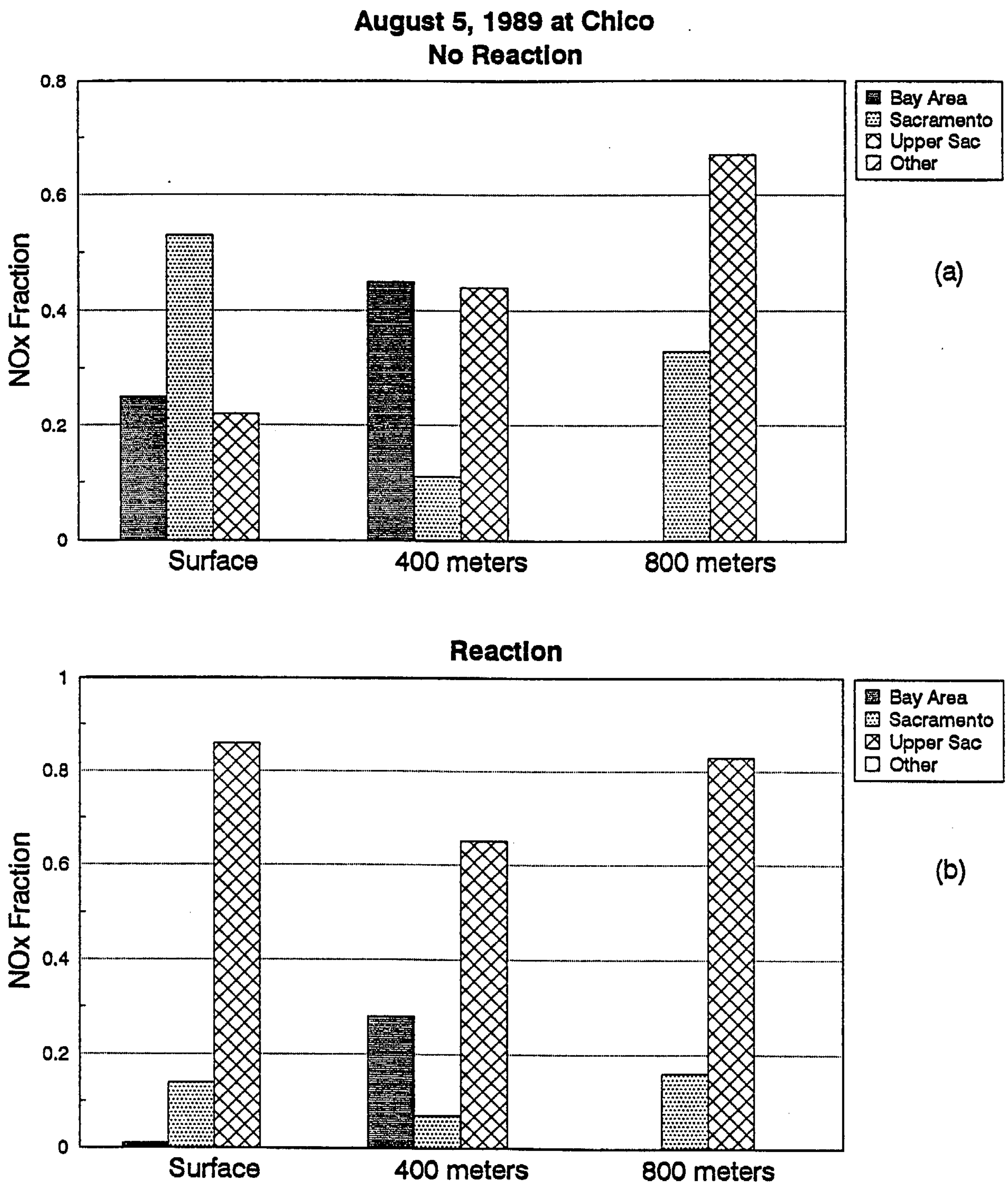


Figure 2-41. NO_x Emissions Contribution Estimates Without Reaction (a) and With Reaction (b) for Surface, 400 Meter, and 800 Meter Back Trajectories From Chico on August 5, 1990 (Average of Three Trajectories at 1200, 1400, and 1600 PST).

contribution estimates. These results are the average of three back trajectories from Chico on August 5, 1990 beginning at 1200, 1400, and 1600 PST. Example surface, 400 meter aloft, and 800 meter aloft trajectories were previously shown in Figures 2-18, 2-19, and 2-20. The surface and 400 meter aloft trajectories follow a similar path through the Broader Sacramento area and the Bay Area. The 800 meter aloft trajectory originated in the Sacramento area and did not pass through the Bay Area.

The left-hand set of results in the top and bottom of the Figure 2-40 are the ROG results for the three surface trajectories. The 1600 PST surface trajectory results were discussed above and presented in Figures 2-38 and 2-39. The center and right-hand set of results are for the 400 meter and 800 meter aloft trajectories.

Because the aloft trajectories travel much faster than the surface trajectories, the losses of ROG are much less than with surface trajectories. The relative ROG contributions from the Bay Area is increased for the aloft case over the Bay Area ROG contributions for the surface trajectory case. However, the dominant conclusion from Figure 2-40 is that under these transport conditions, the local area is contributing a majority of the accumulated ROG, independent of the trajectory height. This is caused by the biogenics emitted in the Upper Sacramento Valley.

Figure 2-41 summarizes the NO_x precursor contributions for surface and aloft back trajectories from Chico on August 5, 1990. This figure is similar to Figure 2-40, except that it is for nitrogen oxides (NO_x). For NO_x, the relative effects when using aloft instead of surface trajectories and when using no reaction instead of reaction are similar to the effects on ROG contributions. However, some of the magnitudes are modified slightly because without biogenics, there are much lower emissions in the Upper Sacramento Valley. For the cases with reaction, the Upper Sacramento Valley contributes a majority of the NO_x to air parcels arriving at Chico on August 5, 1990.

The above discussion used one day as an example to illustrate the methods that we used to estimate precursor contributions and the effects of various assumptions. However, the relative contributions might be different on other days. Figure 2-42 shows the relative precursor contributions for an average of 21 surface back trajectories from Chico on seven days with high ozone concentrations at Chico. On these seven transport days during 1989, the maximum ozone concentration at Chico was 10 pphm on three days, 9 pphm on two days, and 8 pphm on two days. On some of the days used for this figure, the surface trajectories did not travel all the way back to the Bay Area, but only as far as the Broader Sacramento area.

When reactions are not included for these seven days in 1989, Figure 2-42a shows that the Bay Area and the Broader Sacramento area had higher estimated NO_x and ROG precursor contributions at Chico than the Upper Sacramento Valley. However, when reactions are included (Figure 2-42b), the Upper Sacramento Valley contributed about one-half of the ROG and one-half of the NO_x, the Broader Sacramento area contributed about one-third of each precursor, and the Bay Area contributed about 15 percent of each precursor. For all cases in the rest of this report, we have used cases with reaction, since this is more realistic than using no reaction.

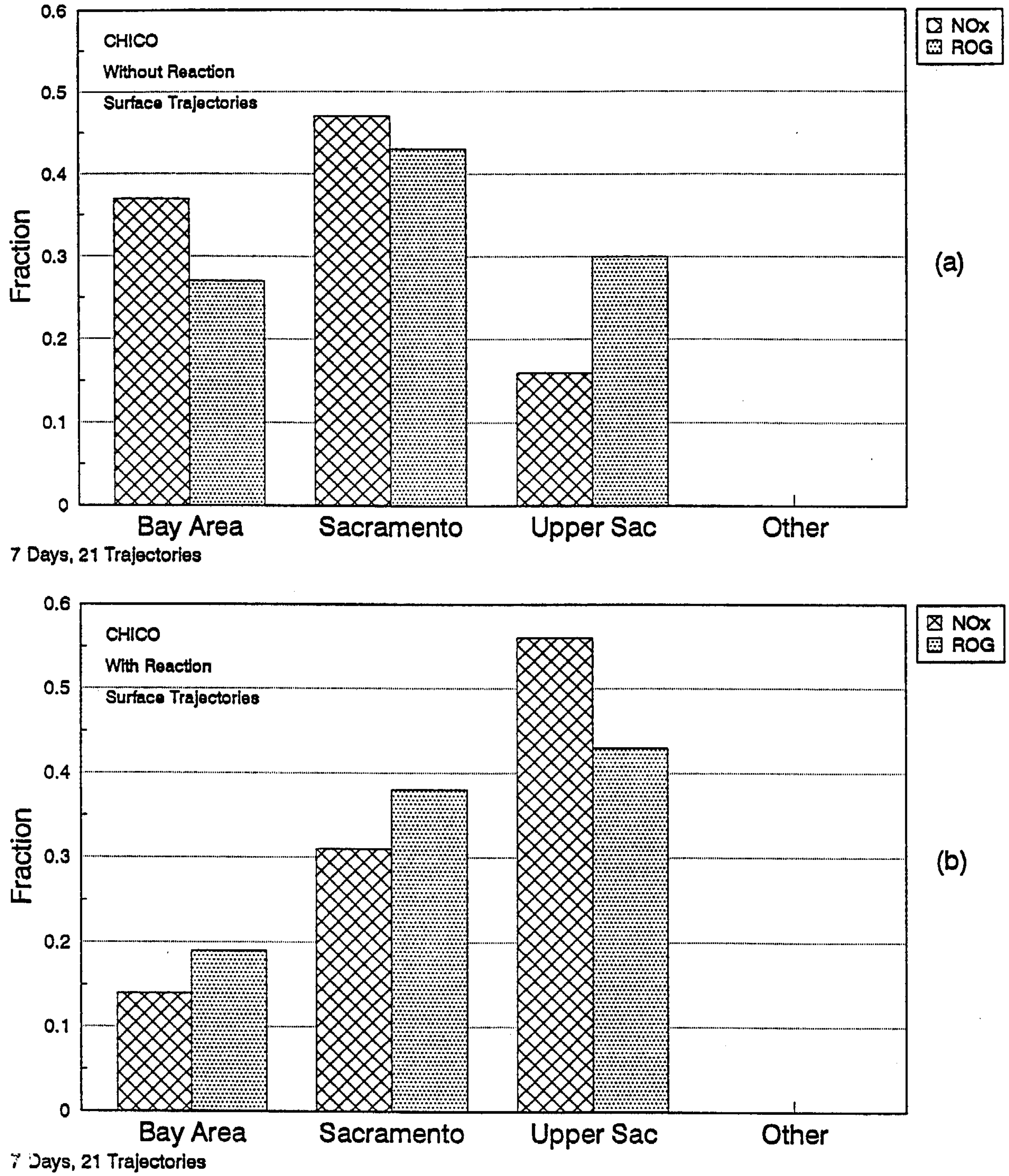


Figure 2-42. Average Precursor Contribution Estimates Without Reaction (a) and With Reaction (b) for 21 Surface Back Trajectories From Chico on Seven Days During 1989.

2.4.3 Precursor Contribution Estimates

This section presents precursor contribution estimates at Upper Sacramento Valley receptor sites for ozone exceedance days at Redding and at Chico. Summaries are presented for precursor estimates for 18 ozone exceedance days at Redding during 1987 and for ten ozone exceedance days at Chico during 1987 and 1988. Estimates for high ozone days at Chico during 1989 were presented in Section 2.4.2. All of these estimates were obtained using surface trajectories; estimates using aloft trajectories were presented in Section 2.2.3.

During 1987, ozone concentrations exceeding the state standard were measured on 20 days at Redding and 15 days at Anderson, just south of Redding. On a few of these days, exceedances occurred at both Redding and Anderson. As a result, ozone exceedances occurred at either Redding or Anderson, or both on 25 separate days. Included were two days with 13 pphm maxima, two days with 12 pphm maxima, and three days with 11 pphm maxima. We performed back trajectories beginning at Redding, Red Bluff, and Chico on 18 of these days, including all of the days with maxima above 10 pphm. These 18 days are listed below in Table 2-3, along with the maximum ozone concentration at either Redding or Anderson and at Chico. Note that only two of these days are also exceedance days at Chico. However, three Chico exceedance days occurred a day before a Redding exceedance.

Table 2-3. Redding or Anderson Exceedance Days During 1987 Selected for Trajectory Analysis and Maximum Ozone Concentrations

1987 Date	O_3 Max (pphm) at Redding or Anderson	O_3 Max (pphm) at Chico
June 3	10	11
June 26	13	10
June 27	10	9
July 13	10	8
July 14	11	9
July 15	10	8
August 4	11	9
August 8	11	9
August 9	10	7
August 31	10	9
September 1	13	8
September 2	10	8
September 3	10	8
September 9	12	9
September 19	10	9
September 23	12	8
October 2	10	9
October 3	10	8

For the 18 exceedance days in 1987 at either Redding or Anderson, we used the surface trajectory results to classify that exceedance as either local (trajectory stayed within about 75 km) or transport (trajectory arrived from beyond about 75 km). The summary results are shown in Table 2-4 below. The Redding exceedances are almost exclusively local with only one three-day episode of transport (July 13-15), whereas at Red Bluff and Chico the same days are about evenly split between local and transport. This result supports the hypothesis that Redding is often separated from the rest of the Sacramento Valley by the convergence zone which forms during the summer between Redding and Sutter Buttes. The convergence zone provides a barrier to transport on many days, at least at the surface.

Table 2-4. Classification of 1987 Redding or Anderson Exceedance Days As Transport or Local at Redding, Red Bluff, and Chico

Monitoring Location	No. of Transport Days	No. of Local Days
Redding	3	15
Red Bluff	10	8
Chico	11	7

These classifications were based on surface trajectories only, thus the air parcels moved slowly and the local area always contributed some precursors. On all transport days both Upper Sacramento and the upwind air basins contributed; thus there were no overwhelming transport classifications. Even though the ARB (1990) did not quantify the definition of overwhelming contribution, we assumed that overwhelming contribution occurred when 80-90 percent contribution was from the upwind basin.

Figures 2-43, 2-44, and 2-45 present average precursor contribution estimates at Upper Sacramento Valley monitoring sites on 18 exceedance days at either Redding or Anderson during 1987. The average estimates are presented for local (a) and transport (b) trajectories at Redding, Red Bluff, and Chico. The 18 days were listed in Table 2-3 and classified as either local or transport for each site in Table 2-4.

For local trajectories arriving at all three sites, the precursor contributions were all from the Upper Sacramento Valley. For transport trajectories at Redding, the northernmost monitoring site, the precursor contribution estimates were over 80 percent from the Upper Sacramento Valley. However, at monitoring sites further south, the contributions for transport trajectories from upwind air basins increased. For trajectories arriving at Red Bluff on these exceedance days, the Upper Sacramento Valley contributed about 60 percent of the NO_x and ROG precursors, with the Bay Area and Broader Sacramento contributing 15-20 percent. For trajectories arriving at Chico, the Upper Sacramento Valley and the Broader Sacramento area contributed 30-40 percent each, with the Bay Area contributing 15-25 percent.

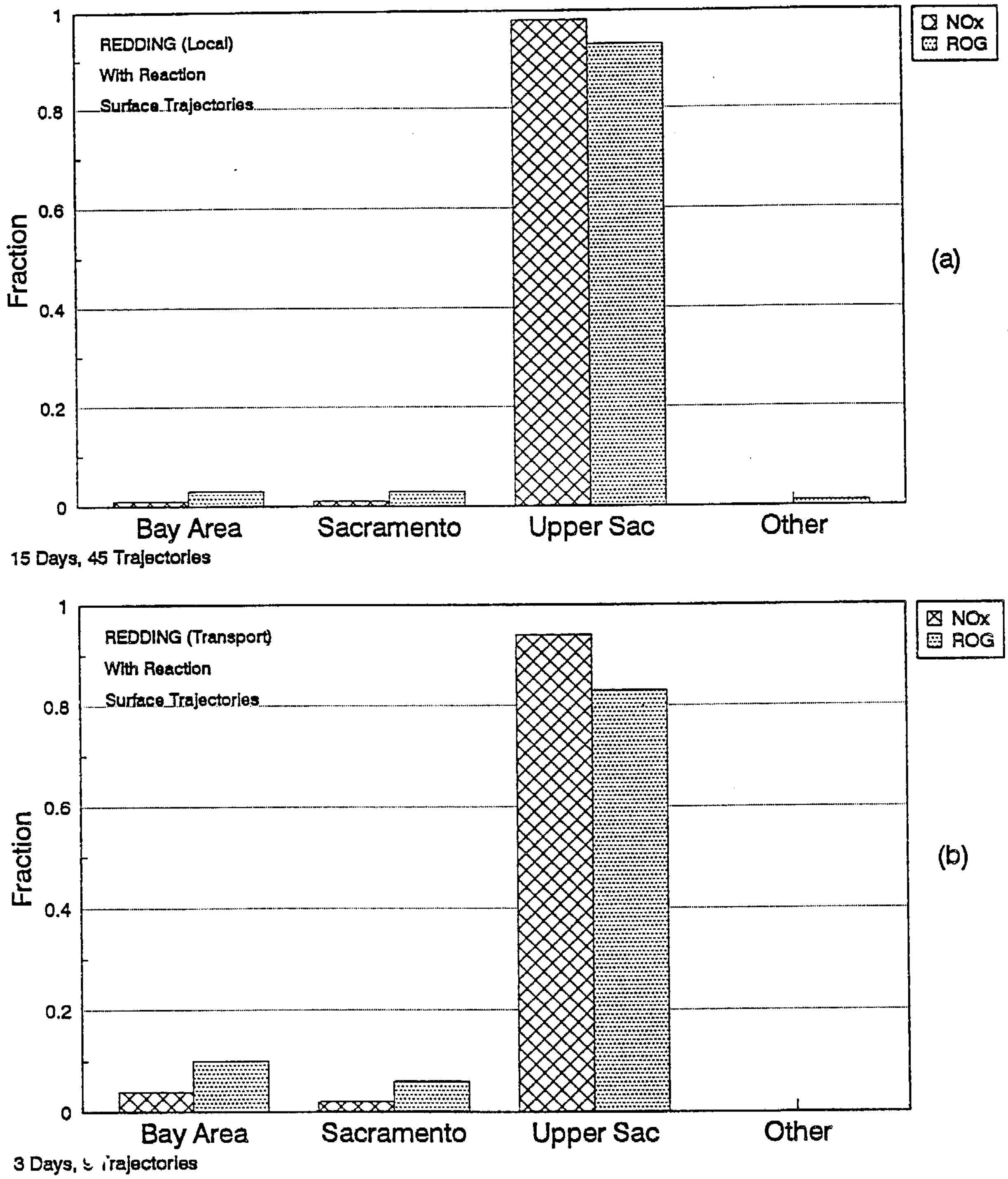


Figure 2-43. Average Precursor Contribution Estimates for Local (a) and Transport (b) Exceedance Days at Redding Using Surface Trajectories (18 Exceedance Days at Either Redding or Anderson During 1987).

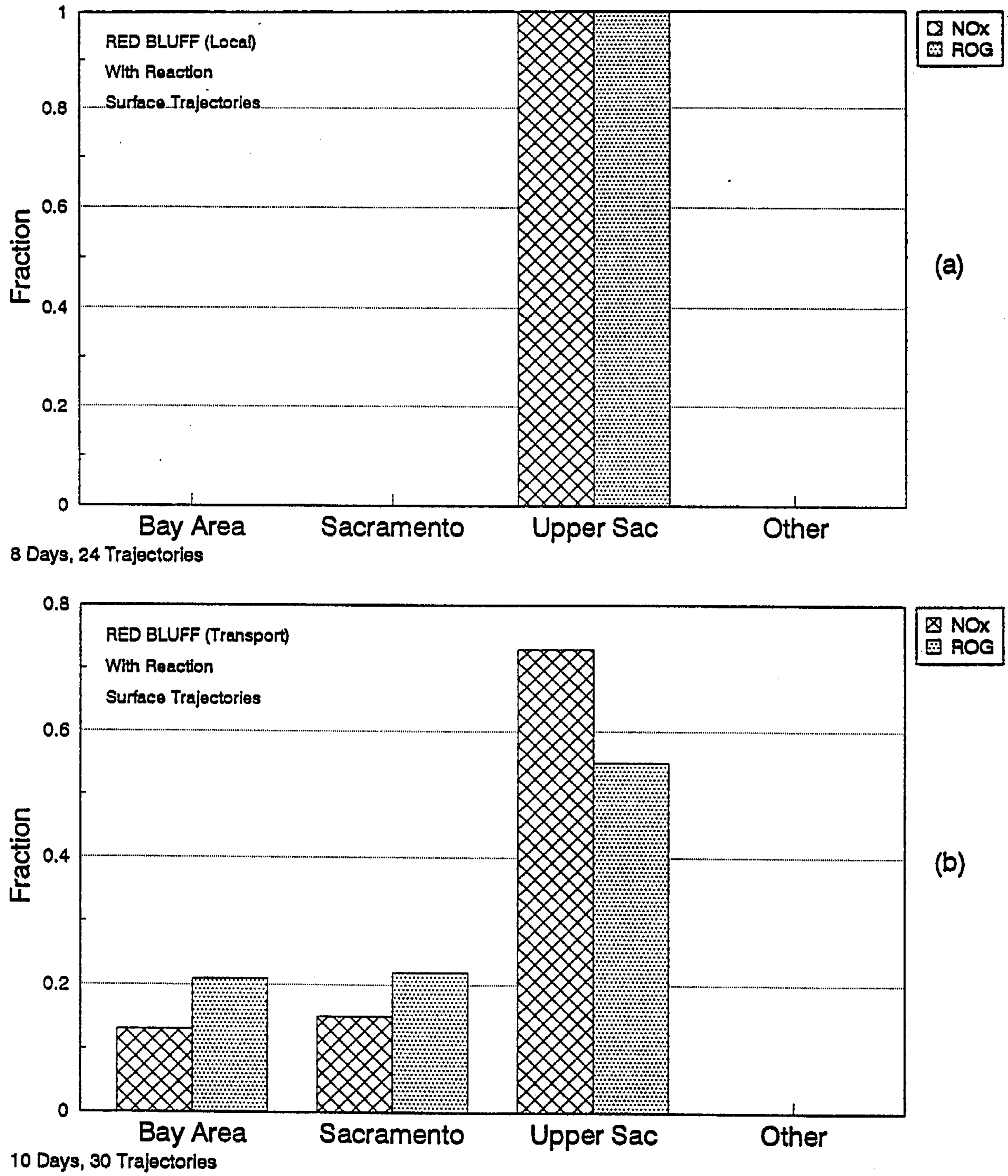


Figure 2-44. Average Precursor Contribution Estimates for Local (a) and Transport (b) Days at Red Bluff Using Surface Trajectories (18 Exceedance Days at Either Redding or Anderson During 1987).

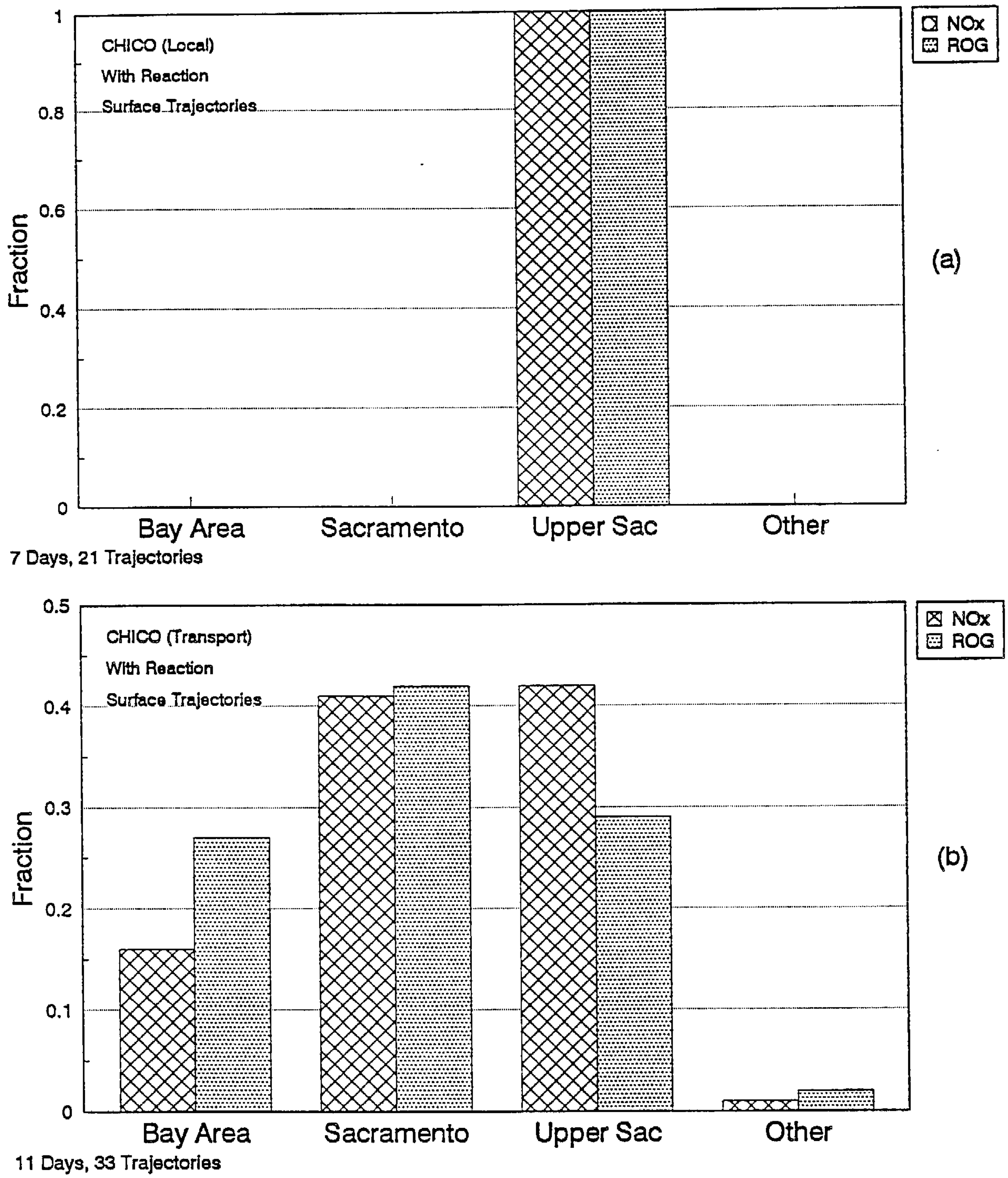


Figure 2-45. Average Precursor Contribution Estimates for Local (a) and Transport (b) Days at Chico Using Surface Trajectories (18 Exceedance Days at Either Redding or Anderson During 1987).

Immediately preceding three of the 1987 Redding exceedance days classified as local at Redding (July 8 and 9 and September 23), there was an exceedance at Chico. For these three days, there might have been the additional possibility of transport aloft to Redding on the subsequent day. This is a weakness with this method when only surface trajectories are used.

During 1987 and 1988 there were 13 state ozone exceedances at the Chico monitoring site; five in 1987 and eight in 1988. All maximum concentrations were 10 pphm. We performed trajectory and precursor contribution estimates for ten of these 13 exceedances. Of those ten, four were local and six were significant transport. The average contributions for the six transport days (18 trajectories) are shown in Figure 2-46. Note that the SFBAAB contributes some precursors, but most of the precursors are from the Upper Sacramento Valley and the Broader Sacramento area.

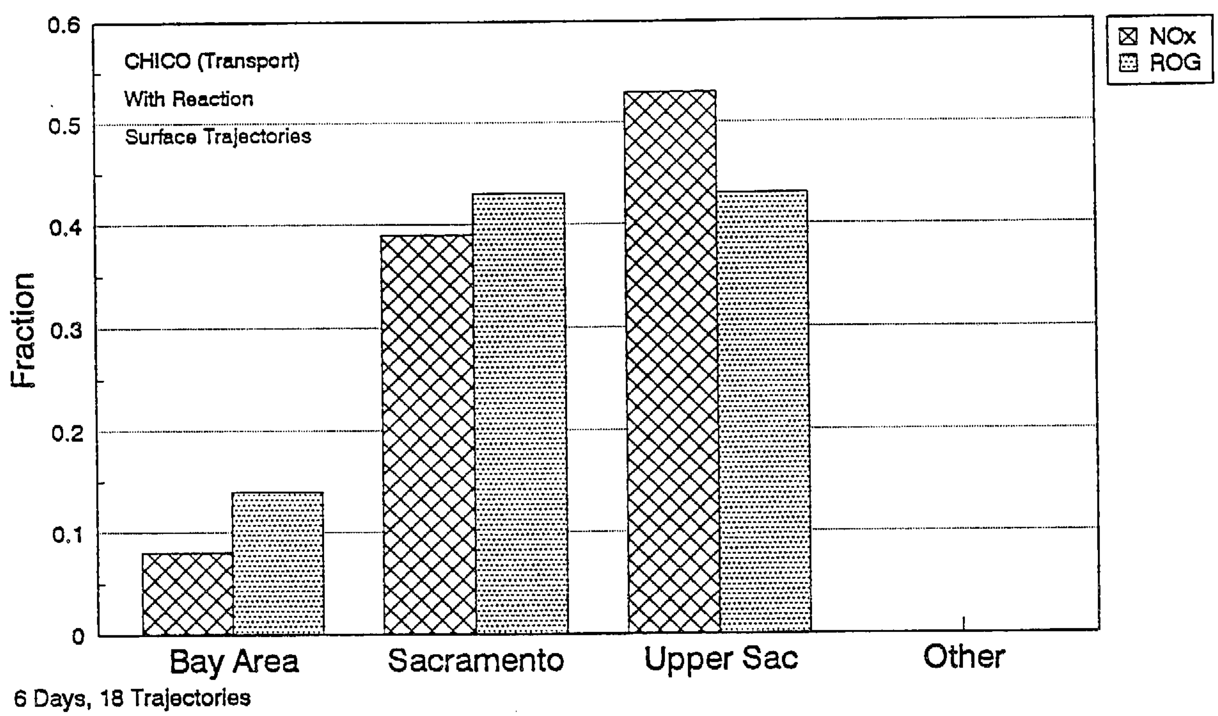


Figure 2-46. Average Precursor Contribution Estimates for Transport Exceedance Days at Chico Using Surface Trajectories (6 Exceedance Days at Chico During 1987 and 1988).

3. TRANSPORT FROM THE SAN FRANCISCO BAY AREA TO THE BROADER SACRAMENTO AREA

This section presents the analysis results for the Broader Sacramento Area (Broader Sac) as the receptor area, including a summary of ozone violations in the area, analysis of air-parcel trajectories and precursor contributions, and a review of past modeling studies. The methods that were used to perform the analyses were discussed in Section 2 and are not repeated here.

The Broader Sacramento area is defined as Nevada County, the Sacramento Metropolitan Air Quality Management District, Yolo-Solano County Air Pollution Control District, and the Sutter, Yuba, El Dorado, and Placer County Air Pollution Control Districts. The major upwind area which might contribute transported pollutants to the Broader Sacramento area is the San Francisco Bay Area Air Basin (SFBAAB). Figure 2-1, a map of the general area which shows these areas, was shown in Section 2.

3.1 FREQUENCY OF OZONE VIOLATIONS IN THE BROADER SACRAMENTO AREA

This section describes the frequency of ozone episodes in the Broader Sacramento Area. The discussion covers ozone episodes by week, using data from long-term monitoring sites in the Broader Sacramento Area for 1978-1988.

Figures 3-1 and 3-2 represent exceedance occurrences at any of a number of sites in the Broader Sacramento Area. The two figures were prepared using ozone data for the following ozone monitoring sites in the Broader Sacramento Area:

Site No.	Broader Sacramento Area Sites
31813	Auburn-DeWitt C Avenue
31810	Rocklin-Sierra College
34293	Citrus Heights-Sunrise
34287	Folsom
34294	North Highlands-Blackfoot
34295	Sacto-Del Pasor Manor
34286	Sacto-Meadowview
48881	Vacaville-Merchant
51897	Pleasant Grove-4 SW
51895	Yuba City Agriculture Building
57577	Davis-UCD Campus
57569	Woodland-W Main Street

These particular sites were used in order to obtain complete records for all years, so that a missing year would not distort the statistics.

Figure 3-1 shows the mean number of days/week when any monitoring site exceeded each of three ozone concentration levels: the State Ozone Standard ($\geq$ 10 pphm), the Federal Standard ($\geq$ 13 pphm), and greater than or equal to

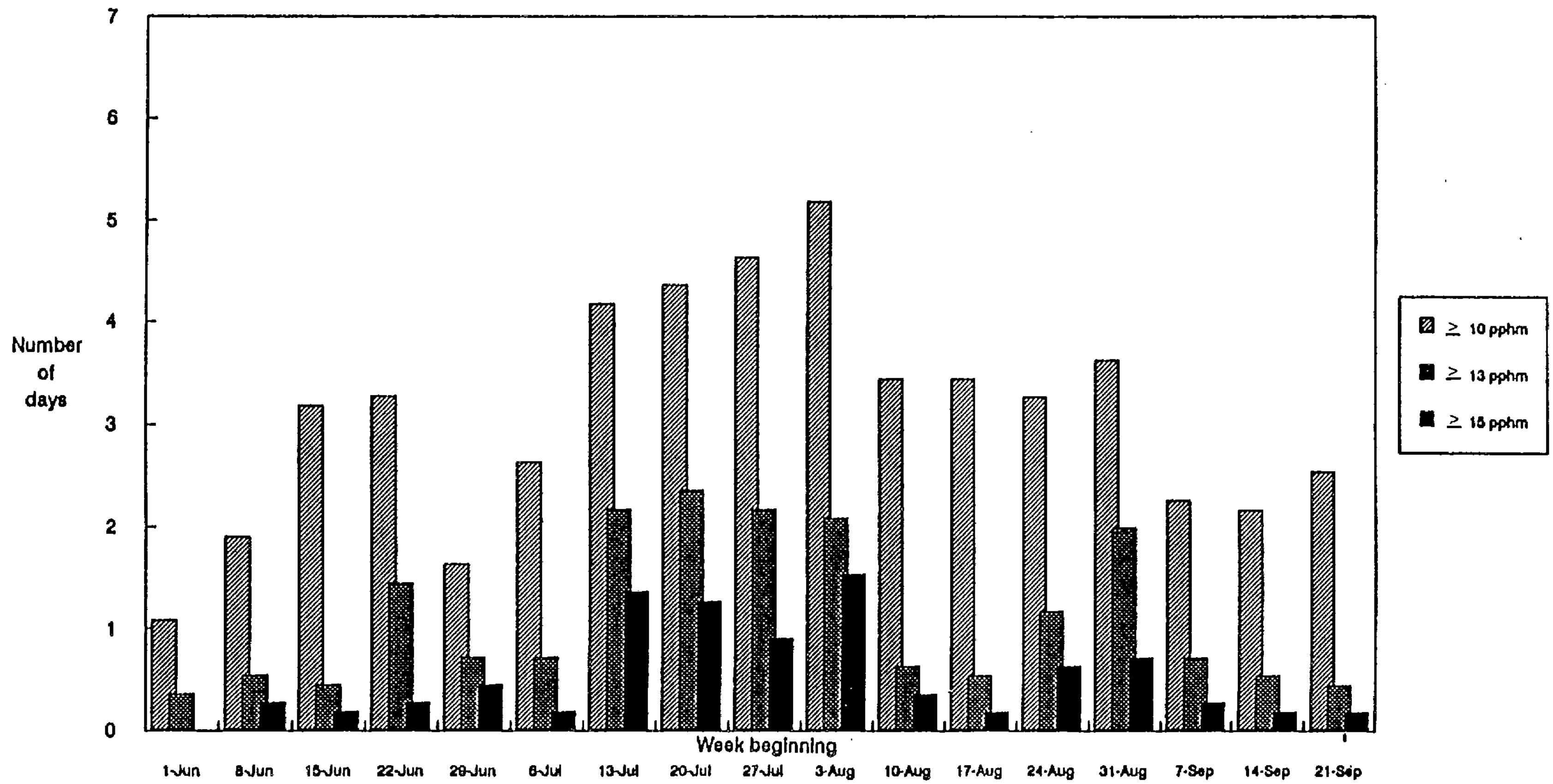


Figure 3-1. Mean Number of Days/Week Peak Ozone Concentration Above Specified Levels for Broader Sacramento Area Sites (1978-1988).

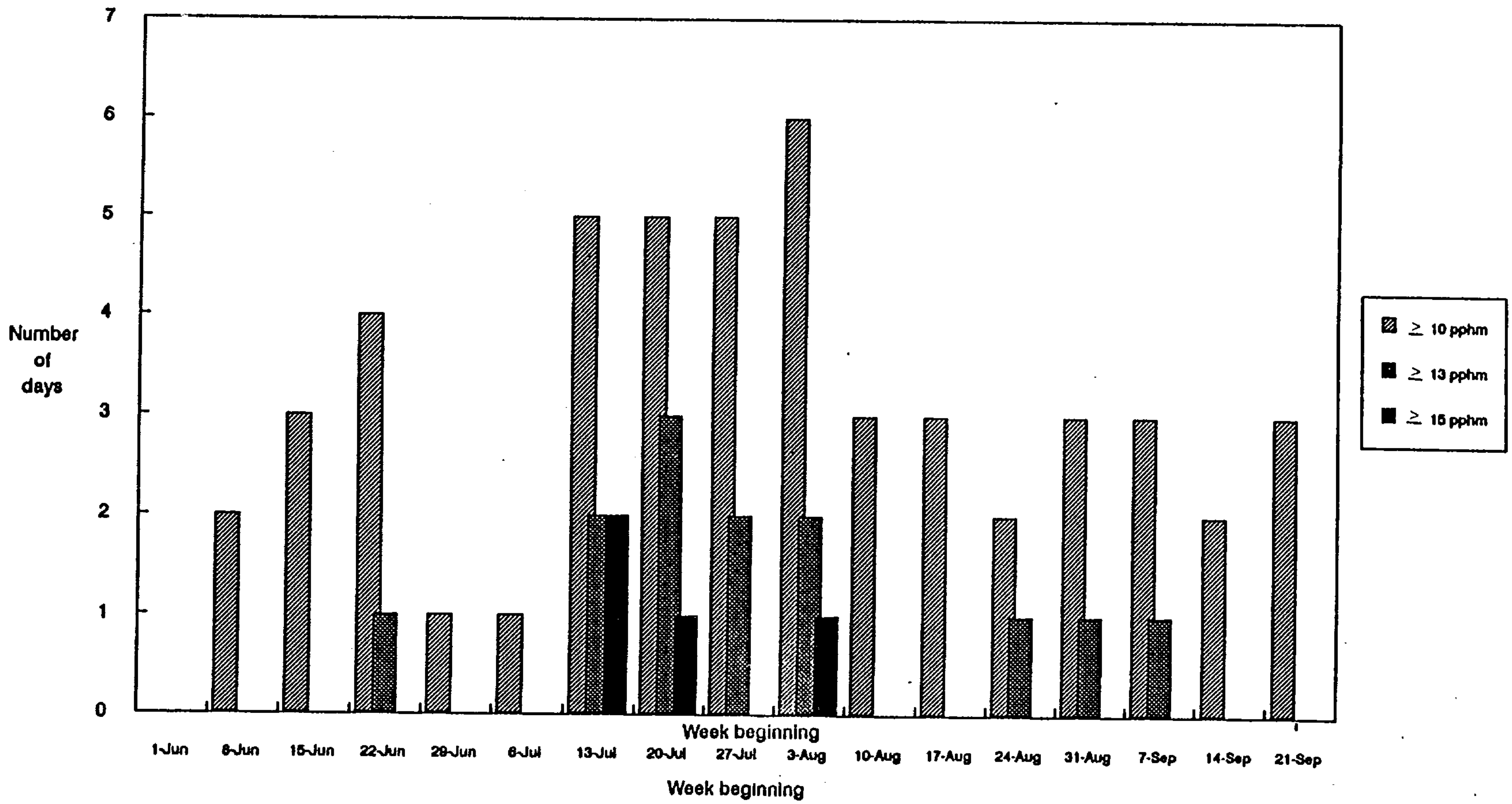


Figure 3-2. Median Number of Days/Week Peak Ozone Concentration Above Specified Levels for Broader Sacramento Area Sites (1978-1988).

15 pphm ozone. The period from June 1 through the end of September has been arbitrarily divided into seven-day weeks that begin on the same date each year.

A similar plot for median values is shown in Figure 3-2. The median is somewhat more stable and does not vary as much as the mean when different years are used in the computations. The data for individual years that were used to generate these plots are presented in tables in the appendix. Note that the data for individual years do vary from the mean and the median values.

Figures 2-1 and 2-2 show similar characteristics:

- There is a general increase in ozone exceedance days, beginning in June and peaking in late-July to early-August; then the number of ozone exceedance days begins to decrease.
- There is a dip in the number of ozone exceedance days around the end of June and in the middle of August.
- The mean and median number of days exceeding the State Ozone Standard is quite high throughout much of the summer: a mean of three or more days/week from June 15 through September 6 and a median of three or more days/week from June 15 through September 27, except for the two weeks from June 29 through July 12.
- However, the mean and median number of days exceeding the Federal Ozone Standard is much lower: a mean and median of one-to-two days/week for about one-half of the weeks from June 22 through September 6.
- The longest period of consecutive weeks with consistently high ozone concentrations begins about the second week of July and continues into September.

However, there is a fairly wide variation in the number of exceedances in a given year. During the individual years 1978-1988, the least smoggy year had only nine days over the State Ozone Standard during the July 6 to September 13 time period. Another clean year had only three days over 14 pphm ozone, while six years had only five days over 14 pphm. In contrast, 1989 had many fewer ozone exceedances. During the 1989 Sacramento field study, there were only six days over the State Ozone Standard during this time period, with only one day over 14 pphm. This demonstrates that there is a significant possibility that a given year might be "cleaner" than an analysis of ten-year conditions might indicate.

3.2 REVIEW OF PAST METEOROLOGICAL, TRAJECTORY, AND AIR QUALITY MODELING STUDIES

Numerous meteorological, trajectory, and air quality modeling studies have been performed for selected areas of California. The objective of these studies was to provide a basis from which to assess the impact of changes in emissions on air quality, as well as an improved understanding of:

- The meteorological processes that are associated with ozone episodes;
- The airflow and transport patterns within a region; and
- The characteristics of ozone episodes.

This section summarizes the results of several past meteorological, trajectory, and air quality modeling studies as they relate to interbasin transport from the San Francisco Bay Area Air Basin (SFBAAB) to the Sacramento Valley, the San Joaquin Valley, and the North Central Coast Air Basin (NCC). The modeling results for transport to the NCC are included here rather than Section 4 because they are interrelated with the results on transport to other areas; however, they are most relevant to the analysis results presented in Section 4.

3.2.1 Review of Modeling Studies of the San Francisco Bay Area

Meteorological modeling of the San Francisco Bay Area Air Basin (SFBAAB) was performed for the Bay Area Air Quality Management District (BAAQMD) by Moore, et al. (1990). Hourly, gridded three-dimensional wind fields were generated using a diagnostic wind model (Douglas and Kessler, 1988) for the periods July 12-13, 1984 and September 30 - October 1, 1980.

The gridded wind fields for July 12 show persistent northwesterly flow. Transport from the SFBAAB to the San Joaquin Valley (SJV) is indicated. The July 13 wind fields, however, show the development of a southerly wind component, which suggests possible transport from the SFBAAB to the lower Sacramento Valley.

The wind fields for September 30 and October 1 are characterized by weak winds and periods of northeasterly flow. The flow patterns for these days suggest the possibility of transport from the lower Sacramento Valley to the SFBAAB, offshore transport from the SFBAAB to the North Central Coast Air Basin (NCC), and inland transport from the SFBAAB (Santa Clara Valley) to the NCC (Hollister).

Surface-layer wind fields for six SFBAAB ozone episodes were generated using a diagnostic wind model (Douglas and Kessler, 1988) for the Western States Petroleum Association (WSPA). The objective of the study was to examine whether intermittent control of refinery emissions during SFBAAB ozone episodes would reduce ozone concentrations in the SFBAAB. A variety of airflow patterns were examined including northwesterly flow, bay outflow, southerly flow, and northeasterly flow (see Hayes, et al., 1984 for a description of these airflow pattern types).

Of the flow patterns examined in this study, the northwesterly flow is conducive to transport from the SFBAAB to the SJV and possibly to the lower Sacramento Valley; bay outflow is associated with stagnation, and a particular transport situation is not evident; southerly flow is associated with transport from the SFBAAB to both the SJV and lower Sacramento Valley; northeasterly flow suggests transport from the Sacramento Valley to the SFBAAB and from the SFBAAB to the NCC. Classification of ozone episodes by airflow patterns indicates that the northeasterly flow regime is quite rare.

A trajectory analysis was also performed as part of the WSPA study. Particle paths computed using the surface-layer wind fields were initiated at six-hour intervals from six SFBAAB refinery locations.

The particle paths indicate that refinery emissions are transported into the SJV under northwest flow conditions (Figure 3-3), into the SJV and lower Sacramento Valley during southerly flow conditions (Figure 3-4), and offshore and southward along the bay during northeasterly flow conditions (Figure 3-5).

Since the particle paths do not incorporate vertical mixing and dispersion, numerous uncertainties are associated with the particle paths derived in the study.

Air quality modeling of the SFBAAB was performed for the BAAQMD by Moore, et al. (1990). Two ozone episodes were simulated: July 12-13, 1984 and September 30 through October 1, 1980. The Carbon-Bond II (CB-II) version of the Urban Airshed Model, UAM, (Reynolds, et al., 1973) was used for the simulations. Base-case simulations were performed for each of the episodes. Further simulations examined the potential impact of Outer Continental Shelf (OCS) development. The modeling domain encompassed the SFBAAB and portions of the NCC. The UAM was exercised with five vertical layers and a horizontal grid spacing of 5 km.

The Federal Standard for ozone was exceeded in the San Francisco Bay Area on both July 12 and 13. Six stations recorded exceedances on July 12 and ten stations recorded exceedances on July 13. The measured daily maximum ozone concentrations were 15 and 16 pphm, respectively. The episode was characterized by onshore flow on both days, with southerly flow developing on the second day.

Results of the base-case simulation for this episode indicate significant overprediction on both days of the episode, with the greatest overpredictions occurring on July 12. On this day, an ozone maximum developed near San Jose between 1000 and 1100 PST. Polluted air from the South Bay is later advected toward Gilroy. However, the simulated concentrations at Gilroy are significantly greater than observed concentrations. A second maxima develops near Richmond between 1400 and 1500 PST and appears to drift southeastward toward the Livermore Valley. A peak concentration of 22 pphm is predicted near Livermore between 1600 and 1700 PST. Transport into the San Joaquin Valley (SJV) via Altamont Pass and Pacheco Pass is indicated on this day.

The base-case simulation produced widespread high ozone concentrations in the SFBAAB on July 13. The ozone appears to develop first near Mt. Hamilton, located to the southeast of San Jose. Northward advection by the southerly flow component followed by eastward advection into the SJV is indicated. Although the winds suggest the possibility, no ozone transport from the SFBAAB into the lower Sacramento Valley is indicated on this day.

A major ozone episode in the Bay Area occurred on September 30 through October 1, 1980. Seven station exceedances were recorded on September 30, and eight exceedances were recorded on October 1. The measured daily maximum ozone concentrations were 19 and 20 pphm, respectively. Winds were light

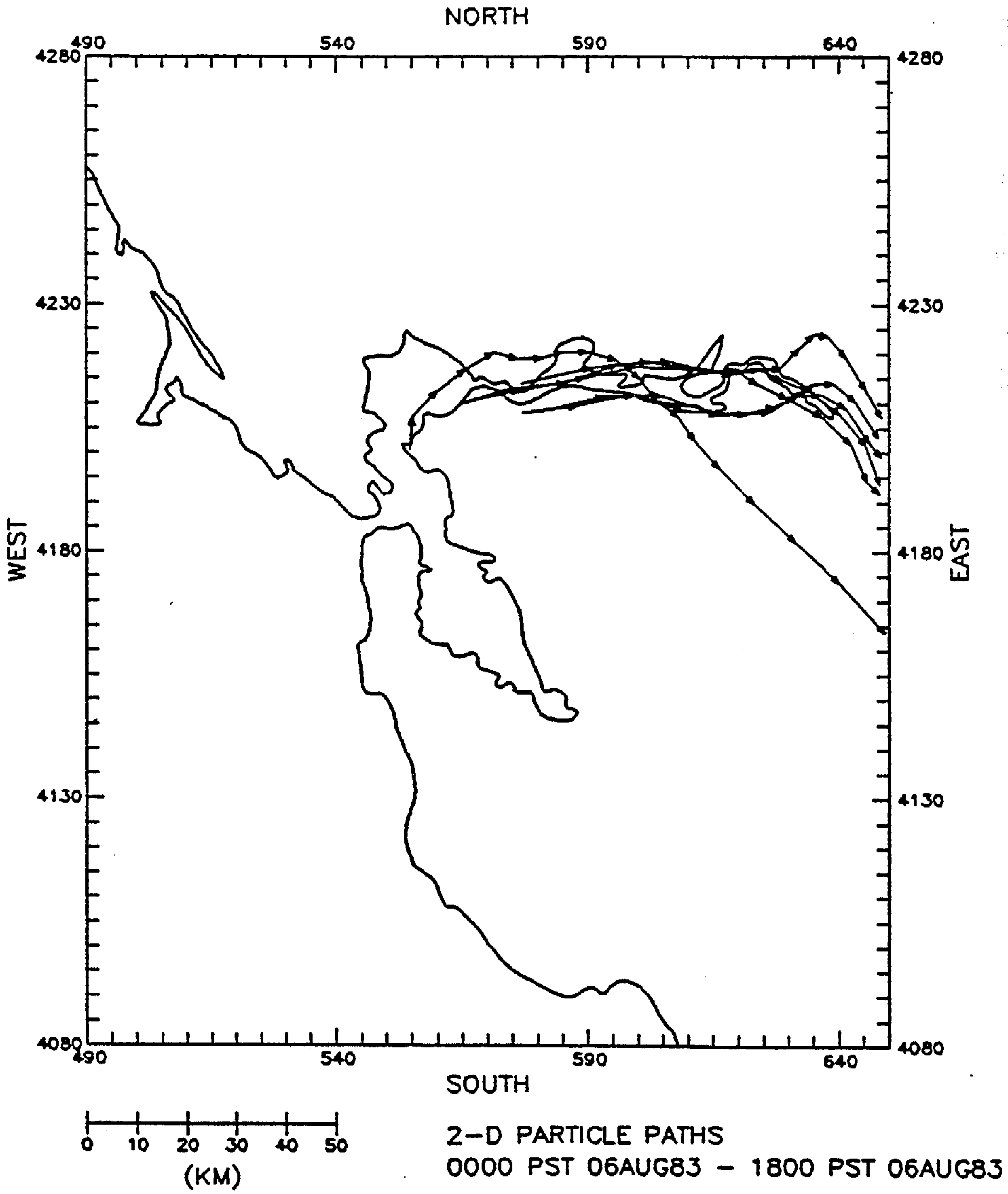


Figure 3-3. Particle Paths Initiated at the Six SFBAAB Refinery Locations at 0000 PST, August 6, 1983 (Northwesterly Flow). Each arrow represents one hour.

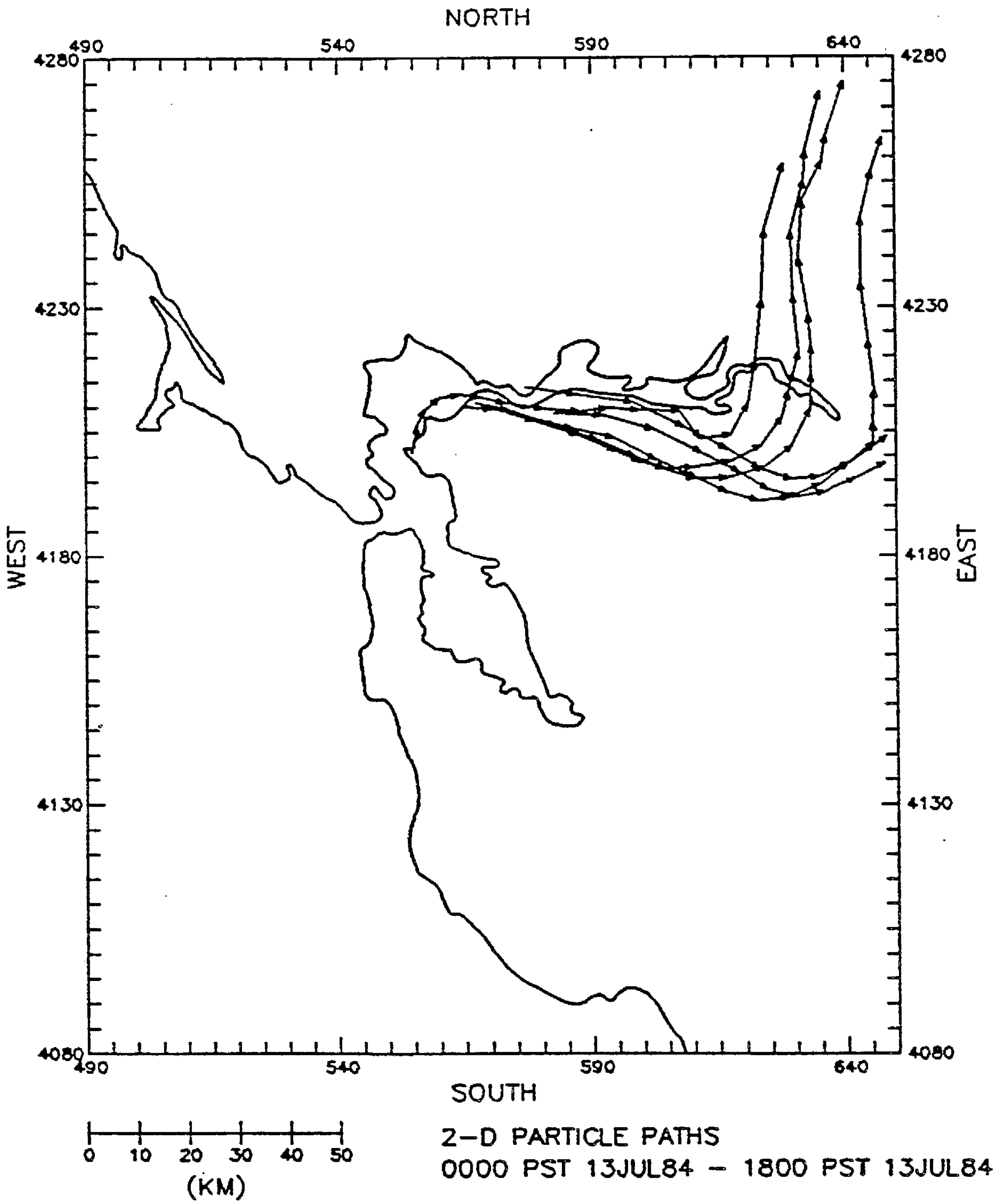


Figure 3-4. Particle Paths Initiated at the Six SFBAAB Refinery Locations at 0000 PST, July 13, 1984 (Southerly Flow). Each arrow represents one hour.

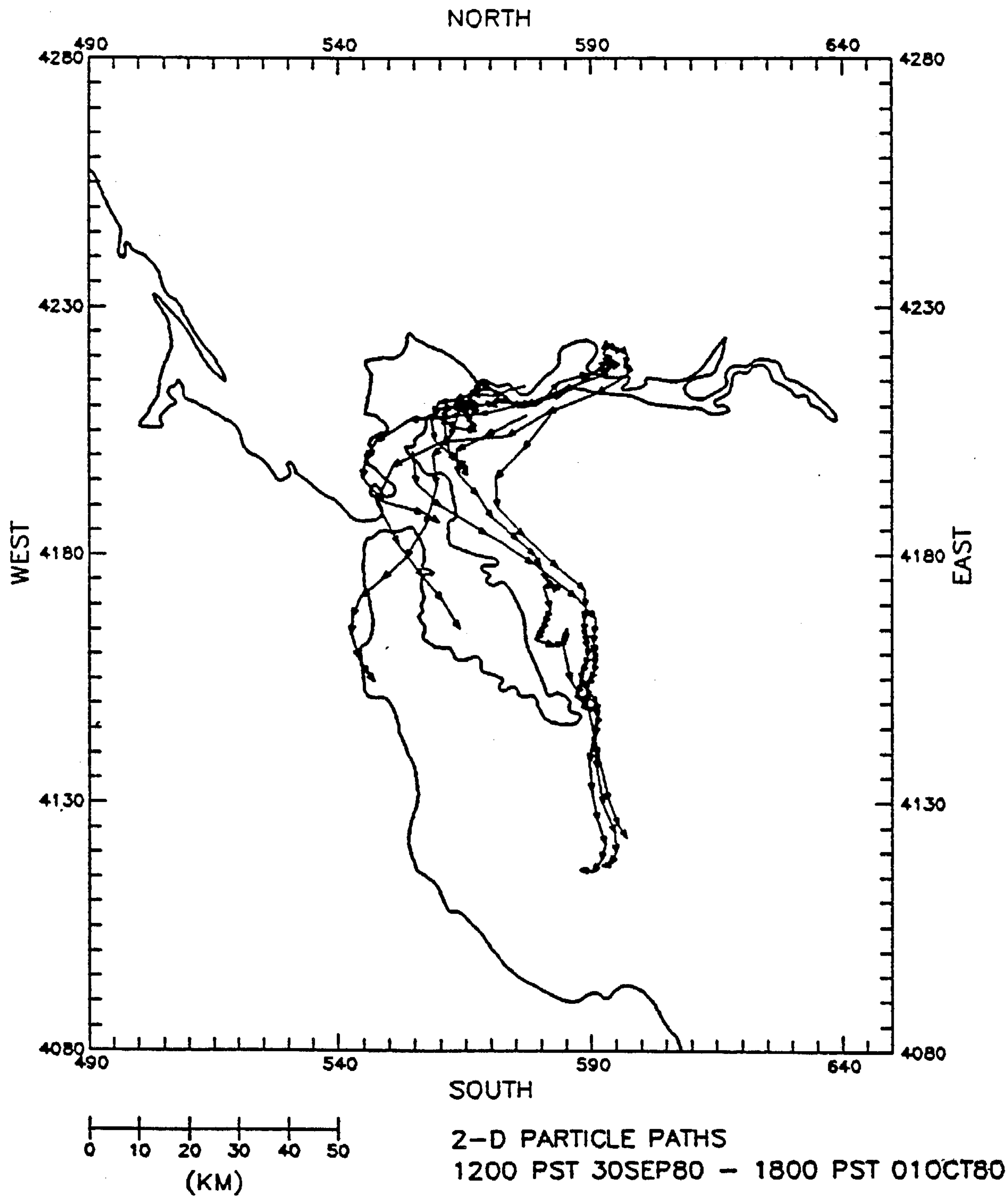


Figure 3-5. Particle Paths Initiated at the Six SFBAAB Refinery Locations at 1200 PST, September 30, 1980 (Northeasterly Flow). Each arrow represents one hour.

during the two-day period, with periods of northeasterly flow. Offshore transport of pollutants from the SFBAAB to the NCC has been documented (Dabberdt, 1983).

Ozone concentrations were significantly underpredicted in the base-case simulation of September 30 - October 1. On September 30, the simulation results indicate transport of ozone and precursor pollutants from the Santa Clara Valley to Gilroy and from the Vallejo-Richmond-San Rafael area offshore. This offshore advection of pollutants due to northeasterly flow is consistent with aircraft observations on this day.

The October 1 base-case simulation indicates that ozone concentrations offshore build and drift southward on this day. Simulated ozone concentrations in the eastern part of the basin are low, while numerous exceedances are indicated along the coast.

In summary, offshore transport of pollutants from the SFBAAB is clearly indicated during the two-day period. Inland transport from the Santa Clara Valley to the Aptos area is also suggested.

Inaccurate simulation of observed ozone concentrations during both episodes was noted. However, offshore and coastal ozone impact locations and timing during the 1980 episode appear to have been simulated quite well. Both observations and simulation results support the existence of offshore transport of ozone and precursor pollutants from the SFBAAB to the NCC.

The OCS-impact-assessment simulations suggest that future proposed OCS activities would have little effect on peak ozone concentrations in the area.

3.2.2 Review of Modeling Studies of the San Joaquin Valley Air Basin and Surrounding Areas

As part of the San Joaquin Valley Air Quality Study (SJVAQS), the Colorado State University Mesoscale Model (CSUMM) (Pielke, 1974; Mahrer and Pielke, 1977, 1978) was used to simulate the airflow in the San Joaquin Valley (SJV) during August 7-8, 1984. The modeling domain encompassed the SJV, the SFBAAB, the NCC,2 and part of the lower Sacramento Valley. Wind fields were generated at nine levels between the surface and 2000 m agl. A terrain-following vertical coordinate was used. Simulation results are described by Kessler and Douglas (1989). The wind fields derived from the prognostic-model simulation did not adequately replicate the available meteorological observations. Specifically, certain features of the airflow such as the Fresno eddy were not resolved.

To improve the agreement between observed and simulated winds, and to improve the resolution of certain airflow features, observations were incorporated into the simulated wind field using an objective-combination procedure (Douglas, 1989). The incorporated data consisted of actual and "pseudo" observations that represented the meteorological conditions in the SJV on August 7-8. The pseudo observations were derived from a subjective analysis of the airflow patterns.

The objective-combination wind fields are described in detail by Douglas (1989). Features of the wind field include:

- Inflow from the SFBAAB through the Carquinez Straits and Pacheco Pass;
- Predominantly up-valley flow in the SJV;
- Development of an eddy circulation in the vicinity of Fresno during the morning hours; and,
- Development of eddies near Sacramento and Bakersfield.

Although inflow from the SFBAAB to the Central Valley is a persistent feature of the August 7-8 objective-combination wind fields, it varies in intensity throughout the day and with height. It is strongest on both days during the late afternoon between the surface and 300 m. Upon entering the Central Valley, the flow splits. The stronger branch is directed up the SJV while the weaker flow is directed into the Sacramento Valley. Flow from the SFBAAB to the lower Sacramento Valley is also depicted in the wind fields as a direct result of the eddy circulation that develops near Sacramento (the Schultz eddy). This nocturnal feature is present through a depth of approximately 300 m.

The wind fields also indicate the possibility of transport from the Sacramento Valley to the SJV during the two-day period. This is especially true at upper levels (700-1200 m).

Finally, eddy circulations within the modeling domain indicate possible recirculation of pollutants during the two day episode.

Particle paths were calculated using the SJVAQS objective-combination wind fields to estimate pollutant transport pathways in the SJV during the August 7-8 period. The particle paths do not incorporate vertical transport or turbulent mixing. Particle paths were initiated at 6-hour intervals beginning at 0000 PST August 7 from Sacramento, Pittsburgh, San Jose, and Stockton. The calculations were discontinued at 1800 PST August 8 or when the particle was advected out of the domain. The particle path analysis is described by Douglas (1989).

The particle paths illustrate some possible pollutant transport pathways. Surface layer particle paths indicate transport from San Jose to the NCC (Hollister area) throughout the period. This is followed by transport into the SJV through Pacheco Pass (Figure 3-6). Particles released from Pittsburgh are advected directly into the SJV. Particle paths initiated at Sacramento are typically carried northward.

Similar patterns are observed aloft with the exception that particle paths initiated at Sacramento at 0000 and 0600 PST are carried into the SJV.

The most comprehensive air quality modeling study of the SJV was performed as part of the SJVAQS (Morris, 1989; Morris and Kessler, 1990). The modeling domain also includes the SFBAAB, the NCC, and the lower Sacramento Valley. Air quality simulations were performed using a variable-grid regional oxidant model (RTM-III). The RTM-III was exercised for August 7-8, 1984. High ozone concentrations were observed in the SJV, the SFBAAB, the NCC, and the lower Sacramento Valley during this period. The variable-grid simulations

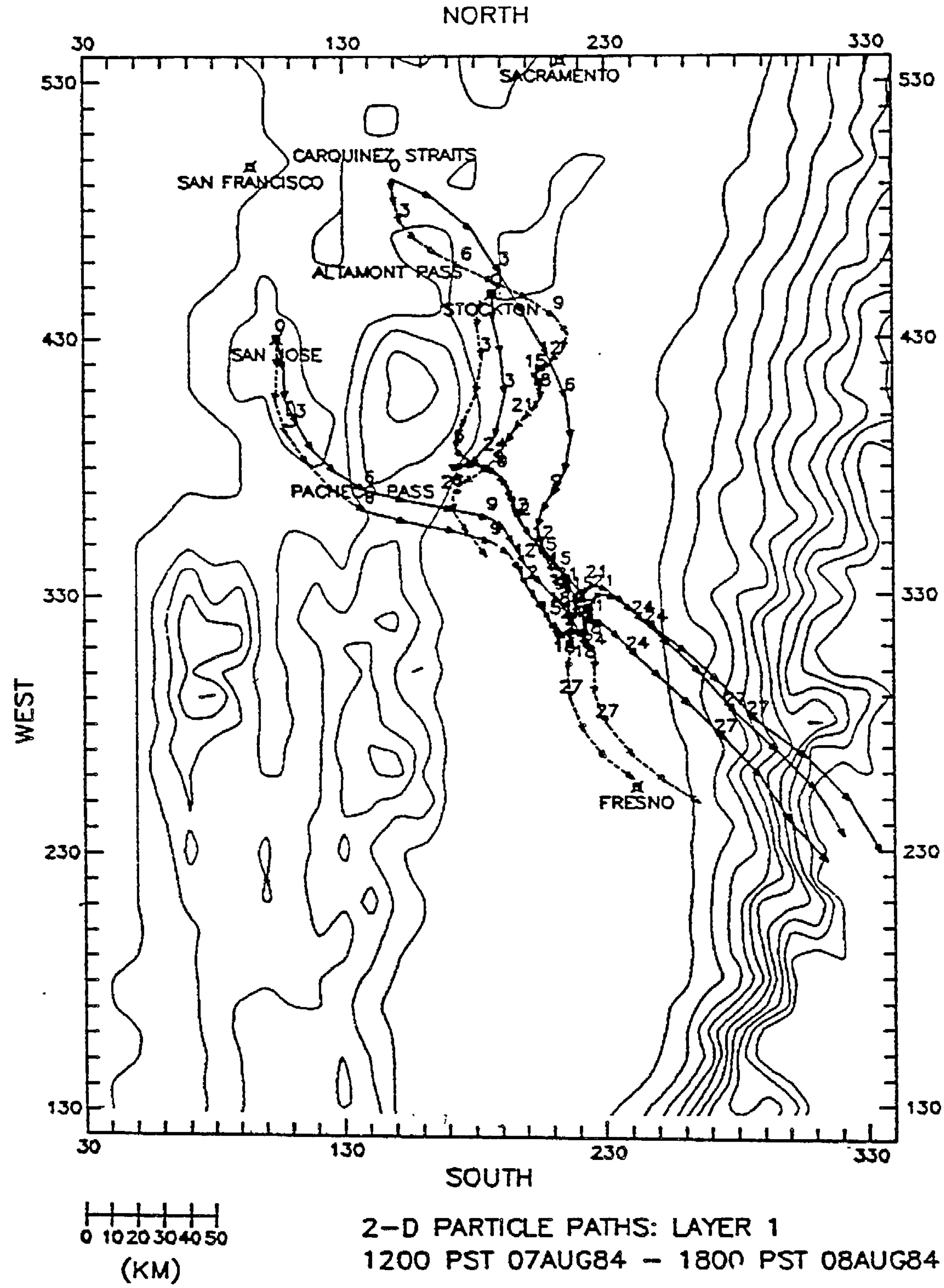


Figure 3-6. CSUMM (Solid) and Objective-Combination (Dashed) 15 m Particle Paths Initiated at Pittsburg, San Jose, Stockton, and Sacramento at 1200 PST August 7, 1984. Each arrow represents one hour. (From Kessler and Douglas, 1989).

consist of a base case and nine sensitivity tests. Simulations were also performed using a fixed-grid version of RTM-III; however, because of better performance with the variable grid, these results are not described here.

The RTM-III was configured with six vertical layers and a horizontal grid spacing that ranged from 5 km in the southern SJV (Fresno and Bakersfield area), 10 km in the northern SJV and the San Francisco Bay Area, 20 km over the remaining coastal and mountainous areas, and 40 km over the ocean. The base-case simulation indicates two distinct pathways for the transport of pollutants between the SFBAAB and the Central Valley: through the Carquinez Straits and through Pacheco Pass. Ozone maxima occur just downwind of these passageways on both August 7 and 8. Combined with airflow into the valley, this suggests transport from the SFBAAB to the lower Sacramento Valley and the SJVAB. Secondary maxima occur near Fresno and Bakersfield. This suggests contributions from local sources as well. Peak observed concentrations are not well simulated; simulated values are lower than observed values on both days. Observed ozone concentrations in the Central Valley increase between August 7 and 8, suggesting day-to-day carryover of pollutants. Simulated values, however, indicate little day-to-day carryover.

Sensitivity tests that are relevant to the issue of transport include:

- Elimination of SFBAAB emissions;
- Use of a different (southerly) wind field on August 7; and,
- Use of clean boundary conditions.

To examine the extent of the influence of SFBAAB emissions on ozone formation in the downwind air basins, a sensitivity test was performed in which all emissions within the SFBAAB were eliminated. Reductions in the daily maximum ozone concentrations on August 7 are on the order of 40 ppb near Sacramento and 50 ppb just downwind of Pacheco Pass. On August 8, the differences decrease to approximately 30 ppb near Sacramento and increase to nearly 70 ppb near Pacheco Pass. Decreases in the daily maximum ozone also occur in the NCC on both days. Slight increases in the daily maximum ozone occur near Stockton and Modesto. The effect of the elimination of SFBAAB emissions is greatest in the northern SJV. However, the influence is noted almost as far south as Fresno on August 7 and south of Bakersfield on August 8.

A sensitivity test was performed to examine the sensitivity of the calculated ozone concentrations to the wind field. The wind field for August 7 was replaced with an alternate wind field. While the original wind field was derived from a prognostic model simulation with large-scale northerly forcing, the alternate wind field was derived from a simulation with southerly forcing. Although the large-scale forcing is southerly, the alternate wind field still indicates flow from the SFBAAB to the Central Valley on August 7. The timing of the inflow is, however, delayed. The ozone concentrations apparently resulting from transport from the SFBAAB are slightly higher and nearer to the SFBAAB. This suggests that the delayed onset of the inflow resulted in higher concentrations but less up-valley transport. Small differences in the daily maximum ozone concentrations on August 8 indicate little day-to-day carryover of pollutants.

To determine the effect of boundary conditions on the simulated ozone concentrations in the modeling region, a sensitivity test was performed in which clean boundary conditions were used. Clean boundary conditions reduced the daily maximum ozone concentrations in the lower Sacramento Valley by approximately 1 pphm on August 8. This indicates that transport into the valley from along the northern boundary during this episode may have influenced the simulated ozone concentrations in the lower Sacramento Valley. The relative contributions from along the northern boundary and the SFBAAB are not clear from these experiments since clean boundary conditions also resulted in a 0.5-0.7 pphm decrease in the daily maximum ozone concentrations in the SFBAAB.

Discrepancies between the observed and simulated ozone concentrations render any conclusions drawn from this study inexact. The sensitivity tests described here indicate that uncertainties in the wind field and boundary conditions can influence the simulated ozone concentrations.

3.3 TRANSPORT-PATH ANALYSES

This section summarizes the results of our trajectory analyses for the Broader Sacramento Area and a discussion of those results. The purpose of these analyses is to evaluate if transport takes place, how often it occurs, and to estimate the general path of pollutant transport to the Broader Sacramento Area (Broader Sac).

To evaluate transport to the Broader Sacramento Area, we selected the domain shown in Figure 2-11, the same domain we used to evaluate transport to the Upper Sacramento Valley. This domain included the receptor sites in the Broader Sacramento Area and the major upwind air basin, the San Francisco Bay Area. We also included the northern part of the San Joaquin Valley in order to complete the wind flow patterns out of the Bay Area and into both the Sacramento and San Joaquin Valleys. We used wind data from 85 surface wind measurement sites. The sites are shown on the map in Figure 2-12 and listed with UTM coordinates in Table 2-2. Data for a few of these sites are limited in duration, such as those sites operated for the SACOG field studies in 1989 and 1990.

We selected ozone exceedance days from the summers of 1989 and 1990 because of the more-extensive meteorological and air quality monitoring performed during the SACOG and SJV/AUSPEX field studies. The selections were based on days with the highest ozone concentrations at Broader Sacramento Area monitoring sites, plus the availability of surface and aloft meteorological data.

We prepared surface wind fields for the Broader Sacramento Area for 6 days in 1989 and 11 in 1990. We then estimated backward trajectories for selected locations and times. We prepared a total of 31 backward surface trajectories. The following discussion illustrates the general characteristics of those trajectories and summarizes the transport results.

Figures 3-7 through 3-10 illustrate various characteristics of the Broader Sacramento Area trajectories. These trajectories are for 1989 and 1990. These trajectories were prepared using surface winds only.

Figure 3-7 shows back trajectories from Sacramento, Rocklin, Auburn, and Colfax for 1400 PST on August 7, 1990; the trajectories for 1200 and 1600 PST were similar. On that day, maximum ozone concentrations were 11 pphm at Rocklin, 14 pphm at Auburn, and 16 pphm at Colfax. The Auburn, Rocklin, and Sacramento trajectories all follow the same path along the route of Interstate 80 from San Francisco through Richmond, Vallejo, and Sacramento; the Colfax trajectory indicates that the arriving air parcels had also passed through San Francisco and Richmond, but had passed south of Sacramento on the way to Rocklin and then along Interstate 80 to Colfax. The Colfax, Auburn, and Rocklin trajectories had spent time over the urban area of Sacramento much of the morning.

Figure 3-8 shows a different transport path for August 8, 1990 at 1400 PST; the trajectories for 1200 and 1600 PST were similar. The Sacramento, Rocklin, and Sacramento Metro back trajectories all indicate that the arriving air parcels had spent most of the previous 20 hours in the Sacramento urban area, including as far west as Davis and Woodland; the previous evening the air parcels had arrived from the SFBAAB. Peak ozone concentrations on this day were 13 pphm at Sacramento and 15 pphm at Sacramento Metro, Rocklin, and Auburn.

Figure 3-9 shows back trajectories from Sacramento, Folsom, and Shingle Springs for 1600 PST on August 3, 1989; the trajectories for 1400 PST were similar. Peak ozone concentrations on this day were 11 pphm at Folsom and 12 pphm at Shingle Springs. Like the trajectories for August 8, 1990, trajectories on this day indicate that the arriving air parcels had spent most of the previous 20 hours in the Sacramento urban area, including as far west as Davis for the Sacramento back trajectory; the previous evening the air parcels had arrived from the SFBAAB.

Figure 3-10 shows back trajectories from Sacramento and Del Paso Manor for 1200 PST on July 12, 1990; the trajectories for 1000 PST were similar. Peak ozone concentrations on this day were 11 pphm at Sacramento and 15 pphm at Del Paso Manor. These trajectories indicate faster transport with a more-westerly component than on the days discussed previously; the air parcels had still passed near Vallejo, but had arrived from the west near Petaluma rather than from the southwest near San Francisco.

In summary, all of these Broader Sac surface back trajectories indicate air parcels arriving from the SFBAAB to the southwest, but some air parcels had moved around slowly in the Broader Sacramento Area for about 20 hours after arriving from the southwest.

3.4 PRECURSOR CONTRIBUTION ESTIMATES

This section presents precursor contribution estimates at Broader Sacramento Area receptor sites for ozone exceedance days during 1989 and 1990. Summaries are presented for precursor estimates for air parcels arriving at

Backward Trajectories from Sacramento, Rocklin, Auburn, and Colfax
14:00 8/7/90 to 00:00 8/6/90

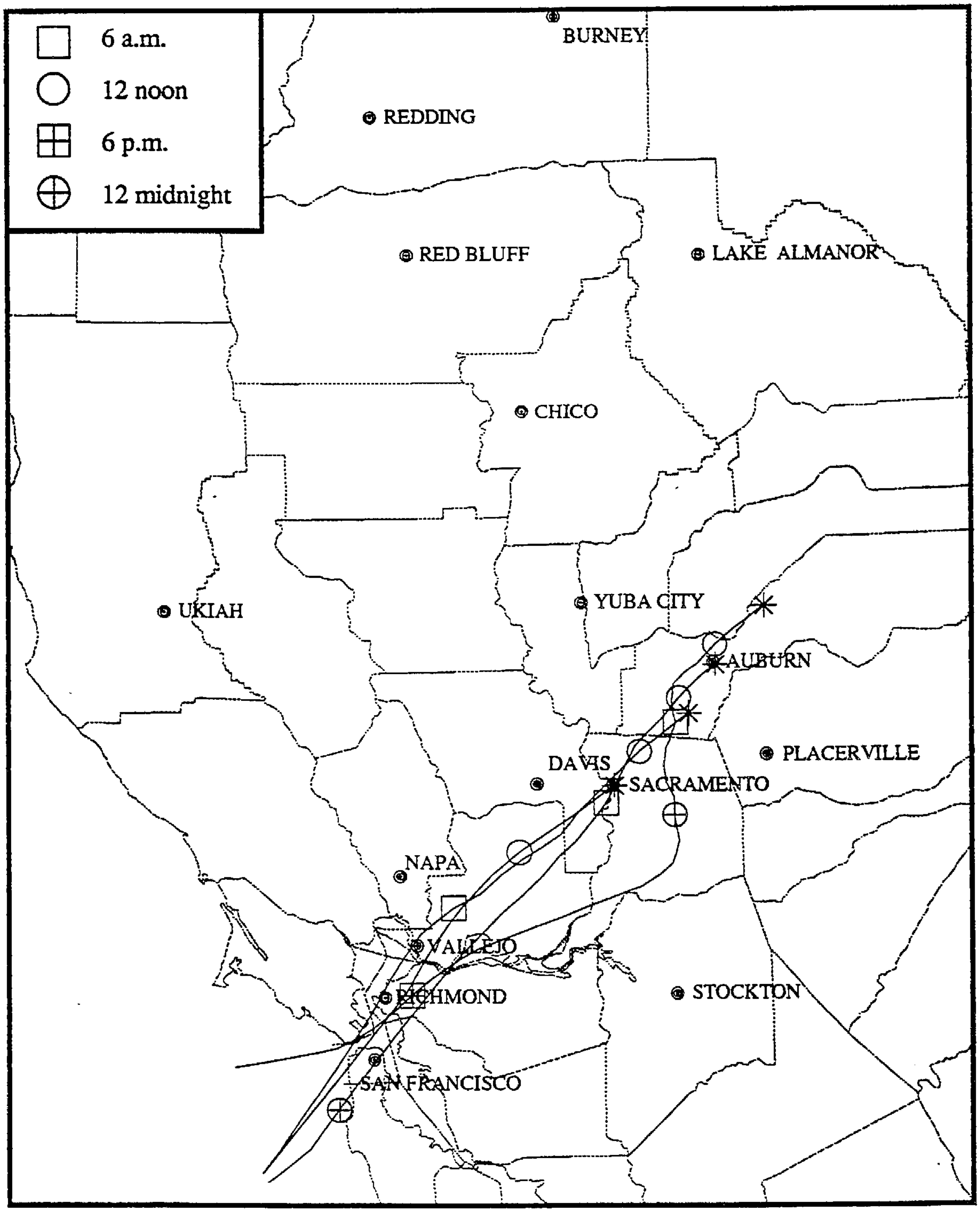


Figure 3-7. Surface Back Trajectories From Sacramento, Rocklin, Auburn, and Colfax on August 7, 1990 Beginning at 1400 PST.

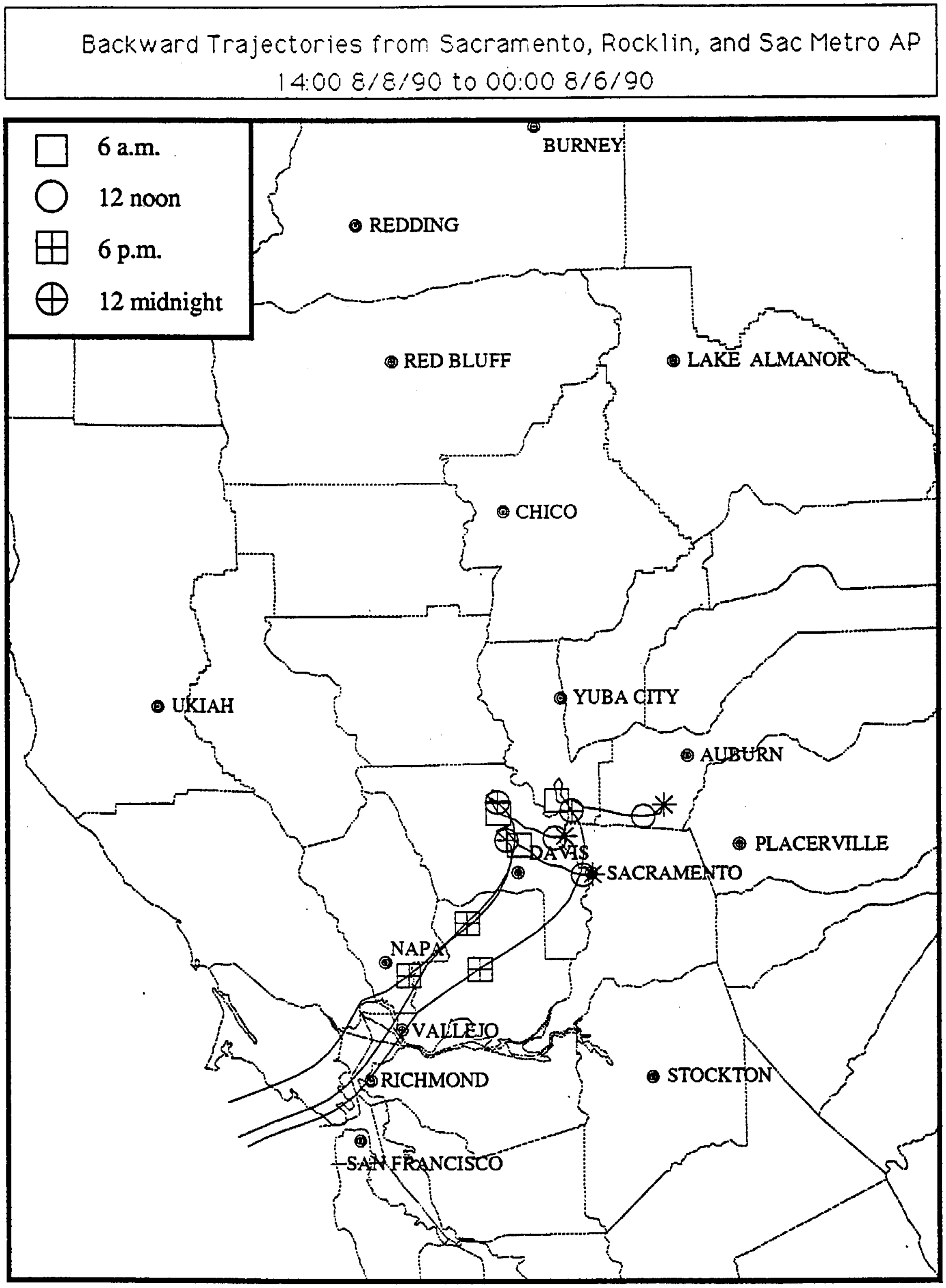


Figure 3-8. Surface Back Trajectories From Sacramento, Rocklin, and Sacramento Metro Airport on August 8, 1990 Beginning at 1400 PST.

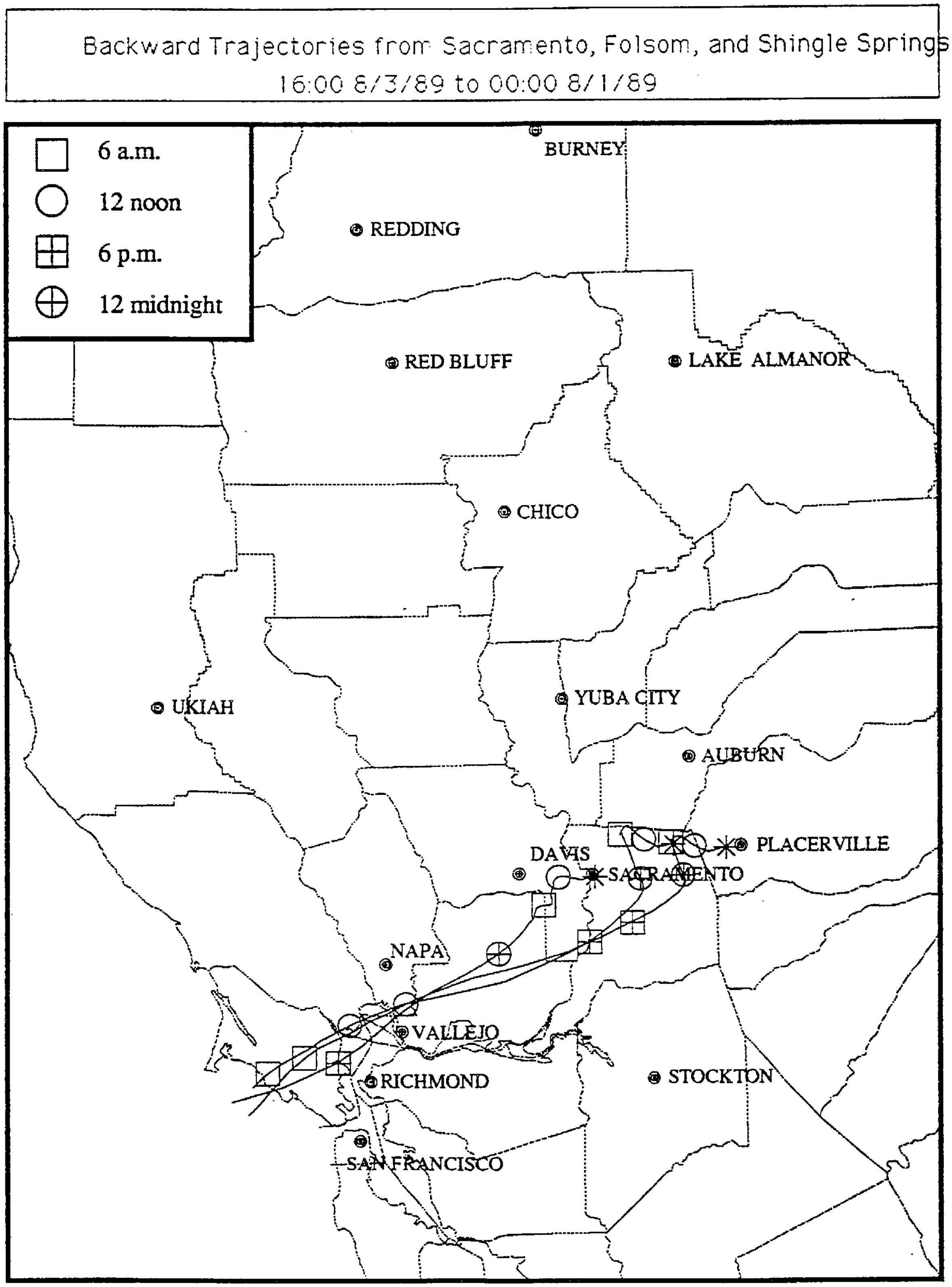


Figure 3-9. Surface Back Trajectories From Sacramento, Folsom, and Shingle Springs on August 3, 1989 Beginning at 1600 PST.

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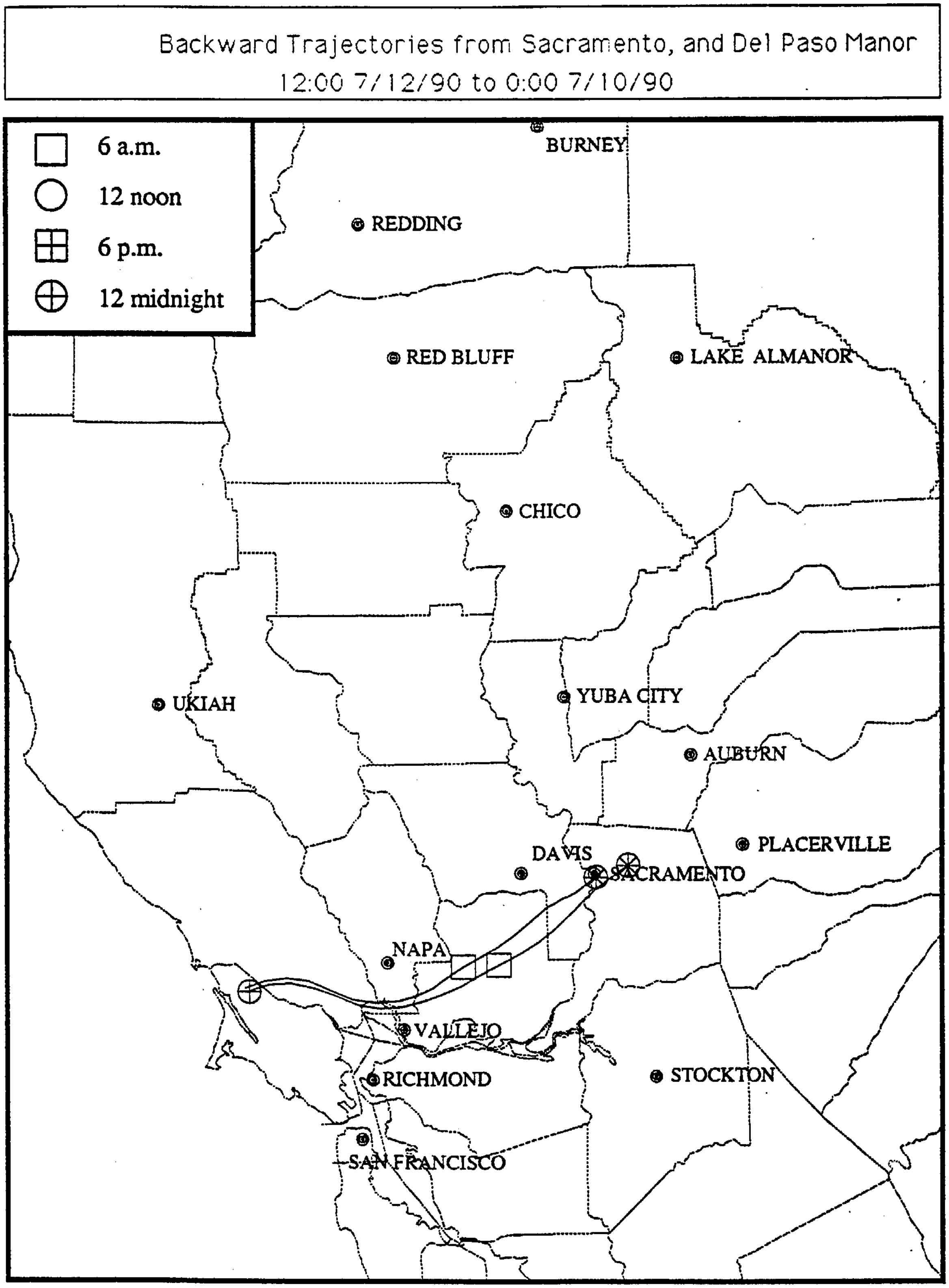


Figure 3-10. Surface Back Trajectories From Sacramento and Del Paso Manor on July 12, 1990 Beginning at 1200 PST.

09-DEC-91

monitoring sites in various parts of the Broader Sacramento Area, including urban Sacramento sites (13 and T, Del Paso Manor, and Rocklin), a near-urban site (Sacramento Metro), and downwind sites along both Highway 50 (Folsom and Shingle Springs) and Interstate 80 (Auburn and Colfax). All of these estimates were obtained using the surface trajectories shown in Figures 3-7 to 3-10.

Figure 3-11 shows the relative NO_x and ROG precursor contributions to air parcels arriving at the Sacramento 13 and T monitoring site on August 7 and 8, 1990. Because the 13 and T monitoring site is near the upwind edge of the Sacramento urban area, a fast-traveling trajectory as shown in Figure 3-7 for August 7 results in a Broader Sacramento Area contribution of about 20 percent. In contrast, the slower-traveling trajectory for August 8 (see Figure 3-8) results in a Broader Sacramento Area contribution of about 80 percent.

A less-dramatic shift in relative contribution occurred for Rocklin on August 7 and 8, 1990 (see Figure 3-12). Because Rocklin is downwind of most of the Sacramento urban area, even the fast-traveling trajectory of August 7, 1990 indicates about 80 percent Broader Sacramento Area contribution. For August 8, 1990, the Broader Sacramento Area contribution is slightly higher and the SFBAAB contribution slightly lower.

Relative precursor contribution estimates are shown for Sacramento Metro Airport (Figure 3-13), Del Paso Manor and Sacramento 13 and T (Figure 3-14), Folsom and Shingle Springs (Figure 3-15), and Colfax and Auburn (Figure 3-16) on various exceedance days during 1989 and 1990: the Broader Sacramento Area contributes from 50 to 90 percent of the NO_x and ROG precursors in arriving air parcels. In general, the local contribution is lower for trajectories arriving at the sites nearest the upwind boundary (13 and T and Sacramento Metro) than for those trajectories arriving at the sites downwind of the Sacramento urban area (Folsom, Shingle Springs, Colfax, and Auburn). No other air basins contributed precursors on these days.

3.5 OZONE AND NITROGEN OXIDES FLUX ESTIMATES

We prepared some simple pollutant flux plots in order to better understand when transport occurred and how much ozone and NO_x were being transported. We calculated a simple relative pollutant flux by multiplying the hourly pollutant concentration by the hourly wind speed in the transport direction. Figure 3-17 shows the relative ozone flux at the Lambie Road monitoring site from June 15 to September 15, 1990.

The Lambie Road monitoring site was operated for the SACOG field studies in 1989 and 1990. The site was located about 10 km east southeast of Travis AFB and was selected to represent a transport path between the SFBAAB and the Broader Sacramento Area. Each point in Figure 3-17 represents one hour during that period; the points are randomly offset within the exact hour in order to allow similar flux values at the same hour to be distinguished. The flux plane has been oriented along a line perpendicular to the most-frequent wind of about 230 degrees; thus we used the resultant wind speed parallel to 230 degrees in our calculation of the pollutant flux.

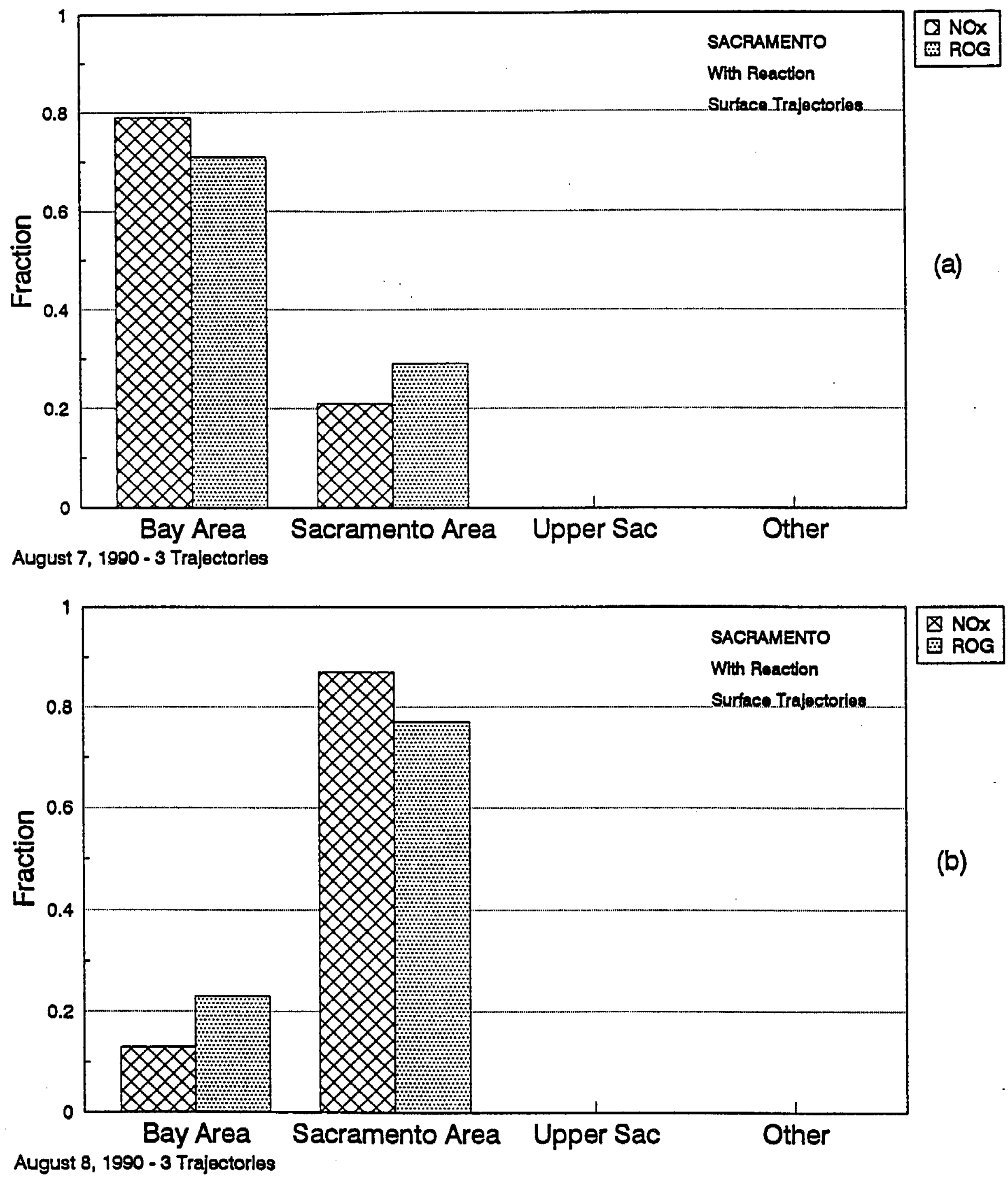
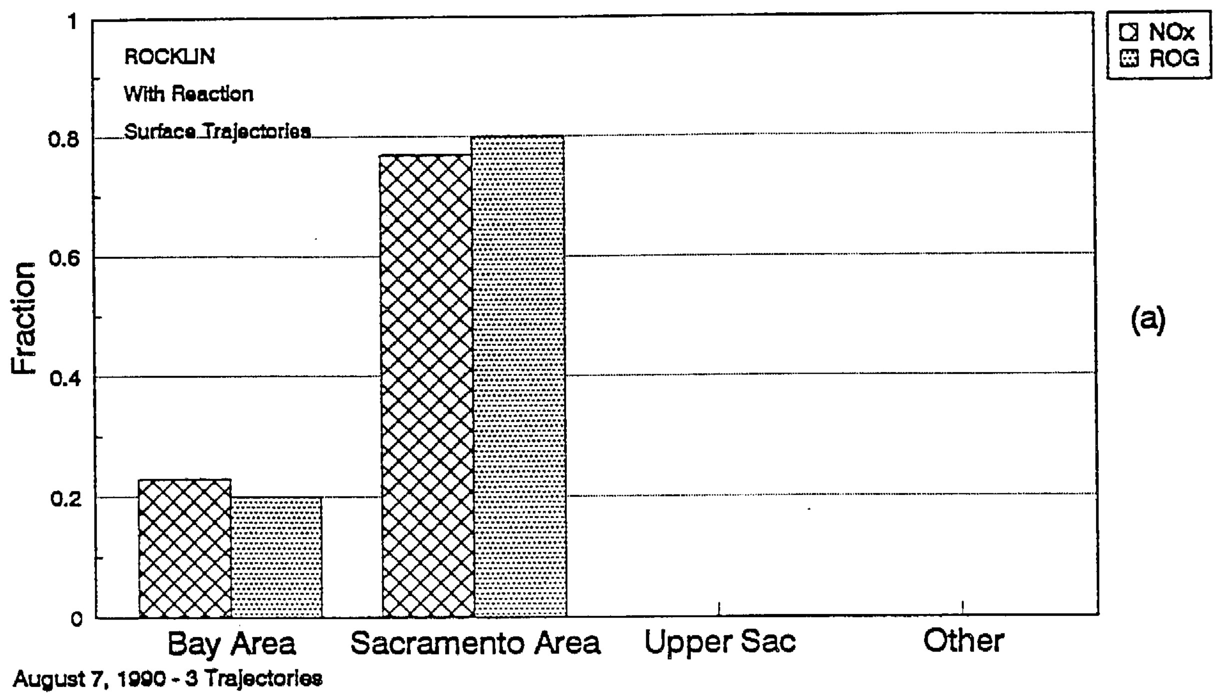


Figure 3-11. Average Precursor Contribution Estimates for August 7, 1990 (a) and August 8, 1990 (b) at Sacramento (13 and T) Using Surface Trajectories.



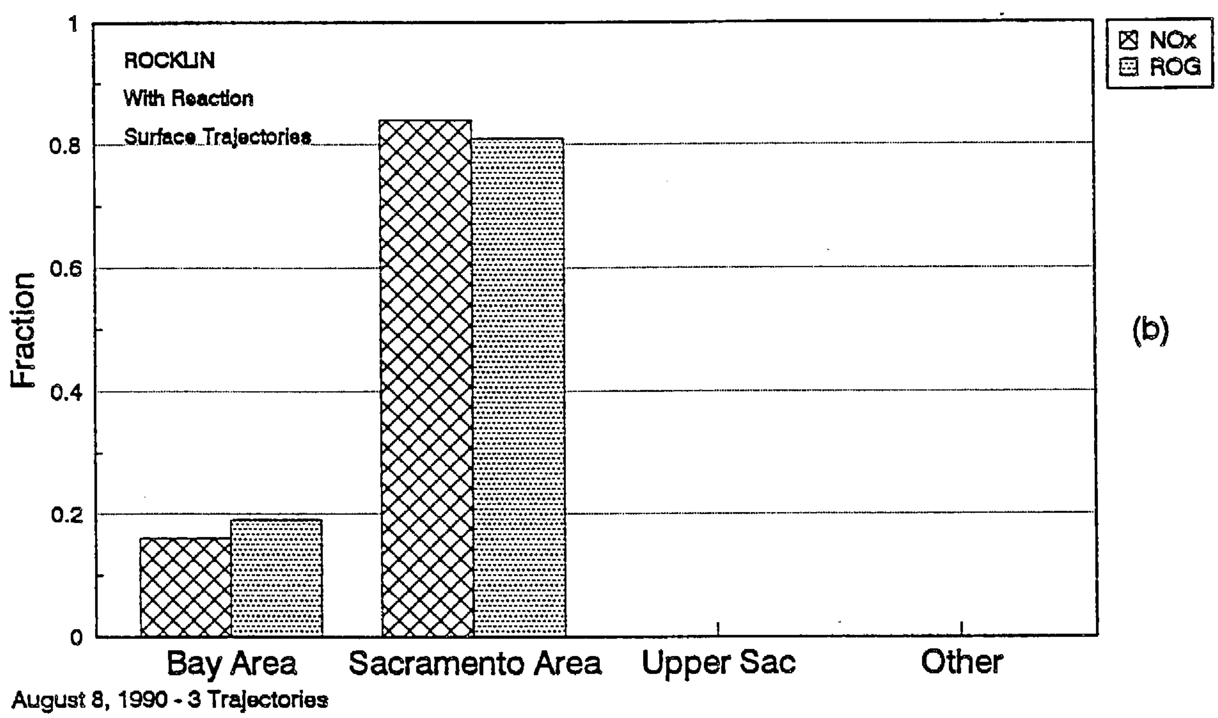


Figure 3-12. Average Precursor Contribution Estimates for August 7, 1990 (a) and August 8, 1990 (b) at Rocklin Using Surface Trajectories.

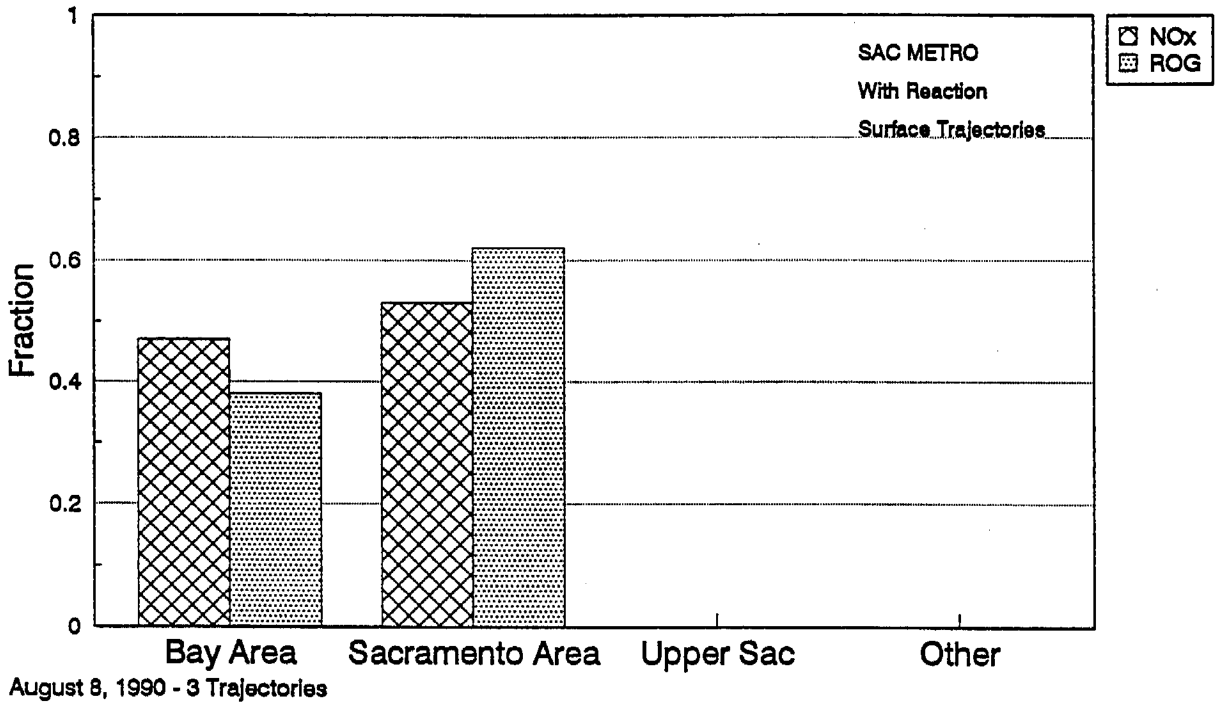


Figure 3-13. Average Precursor Contribution Estimates for August 8, 1990 at Sacramento Metro Airport Using Surface Trajectories.

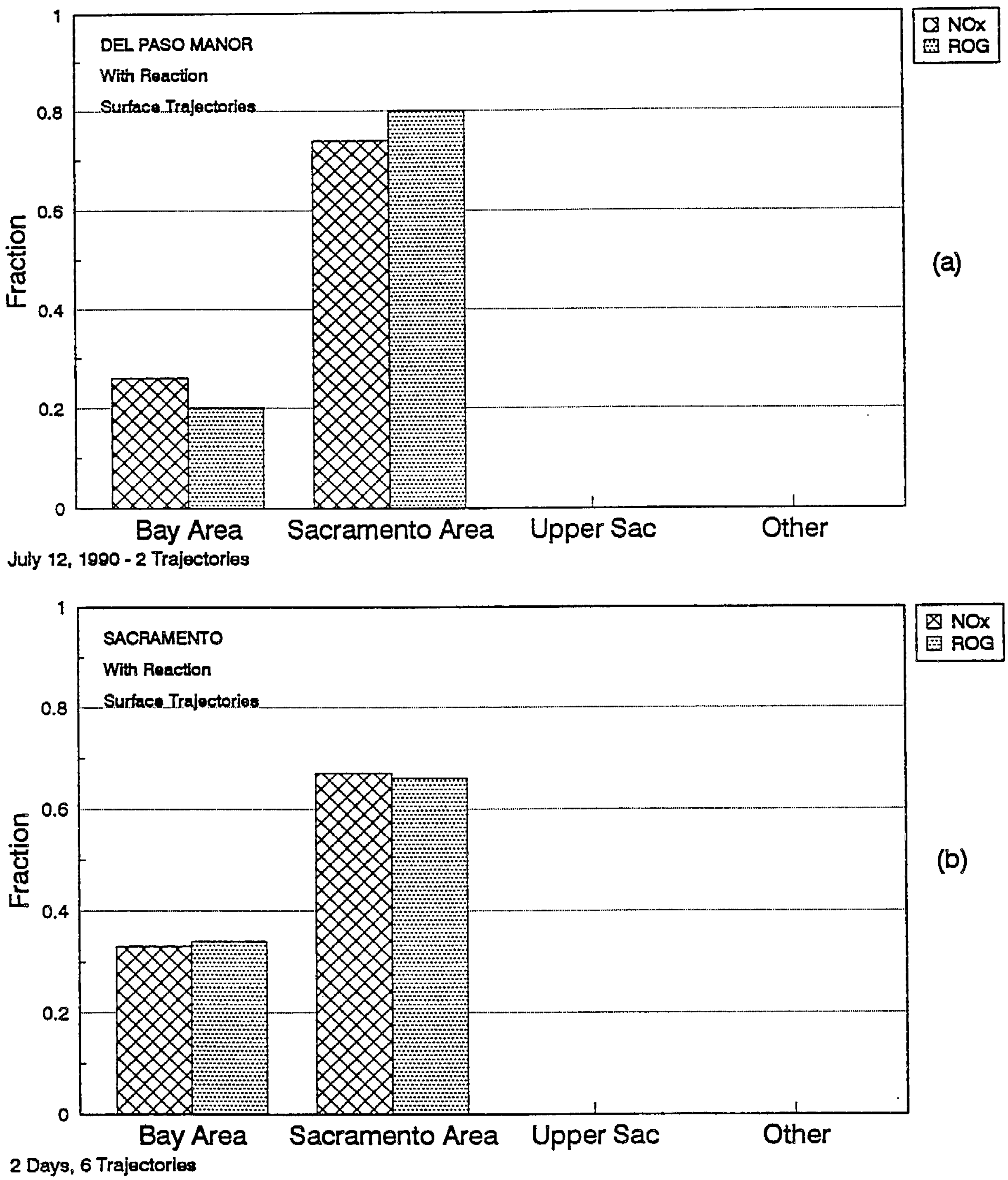


Figure 3-14. Average Precursor Contribution Estimates for July 12, 1990 at Del Paso Manor (a) and for July 12, 1990 and August 3, 1989 at Sacramento 13 and T (b) Using Surface Trajectories.

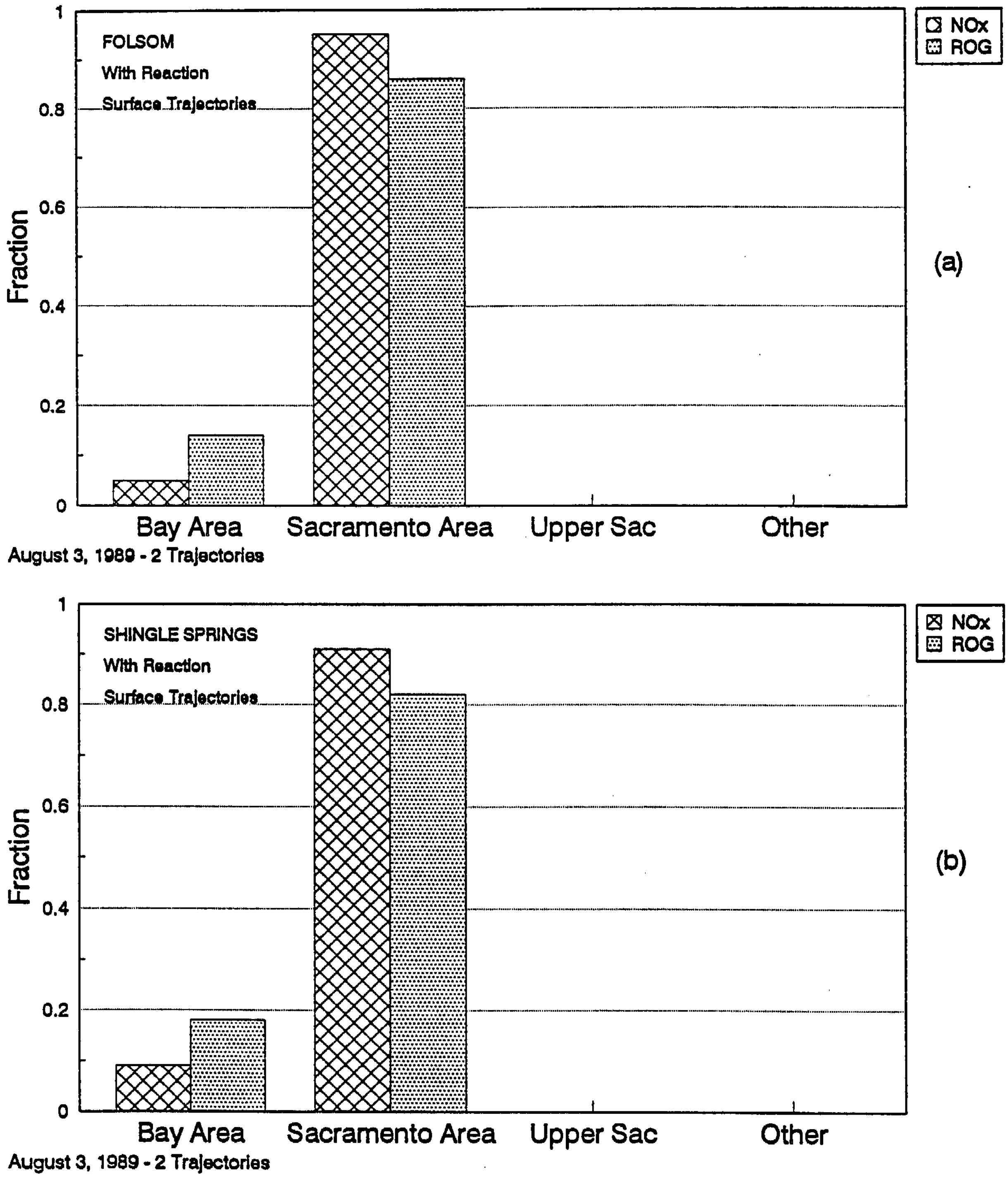


Figure 3-15. Average Precursor Contribution Estimates for August 3, 1989 at Folsom (a) and Shingle Springs (Ponderosa High School) (b) Using Surface Trajectories.

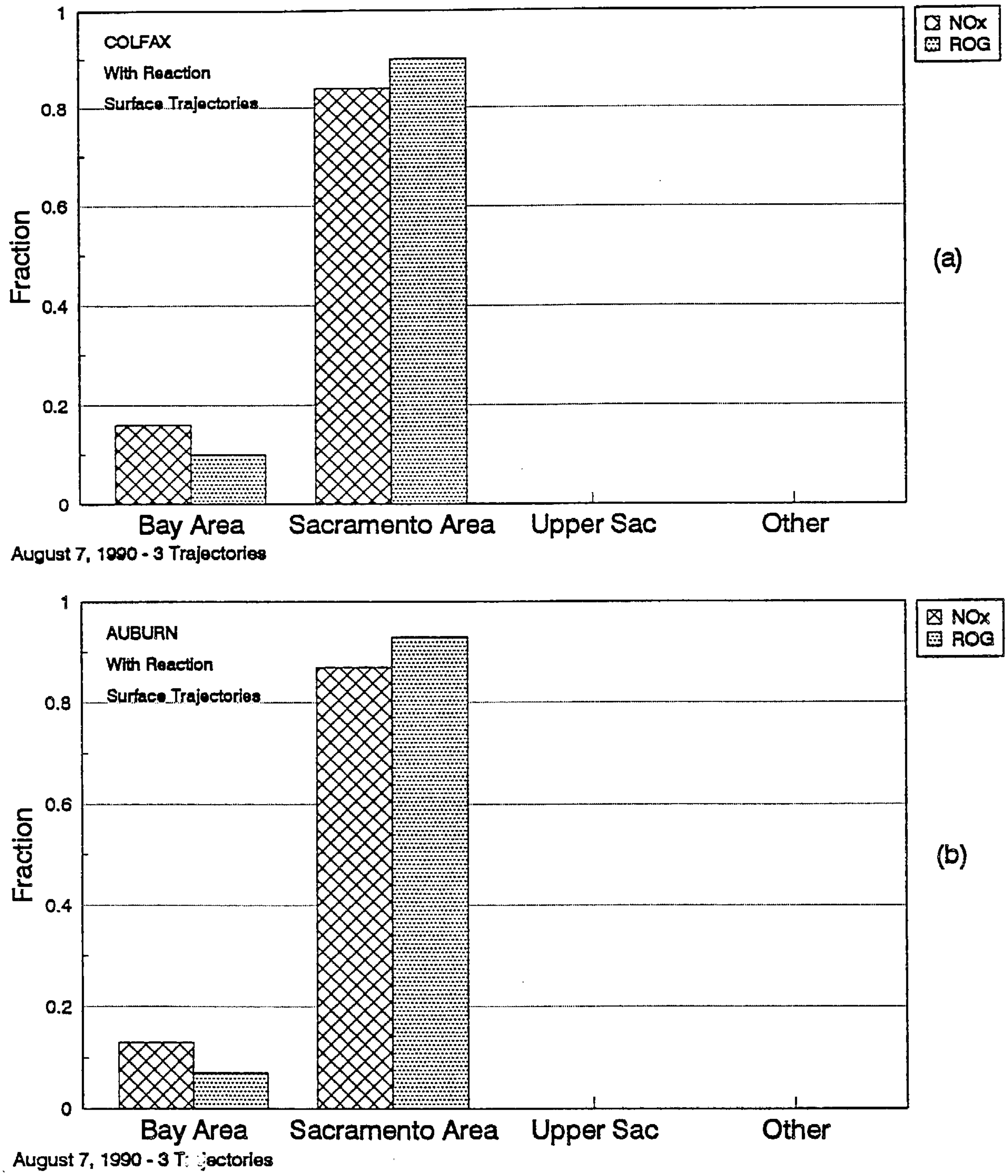


Figure 3-16. Average Precursor Contribution Estimates for August 7, 1990 at Colfax (a) and Auburn (b) Using Surface Trajectories.

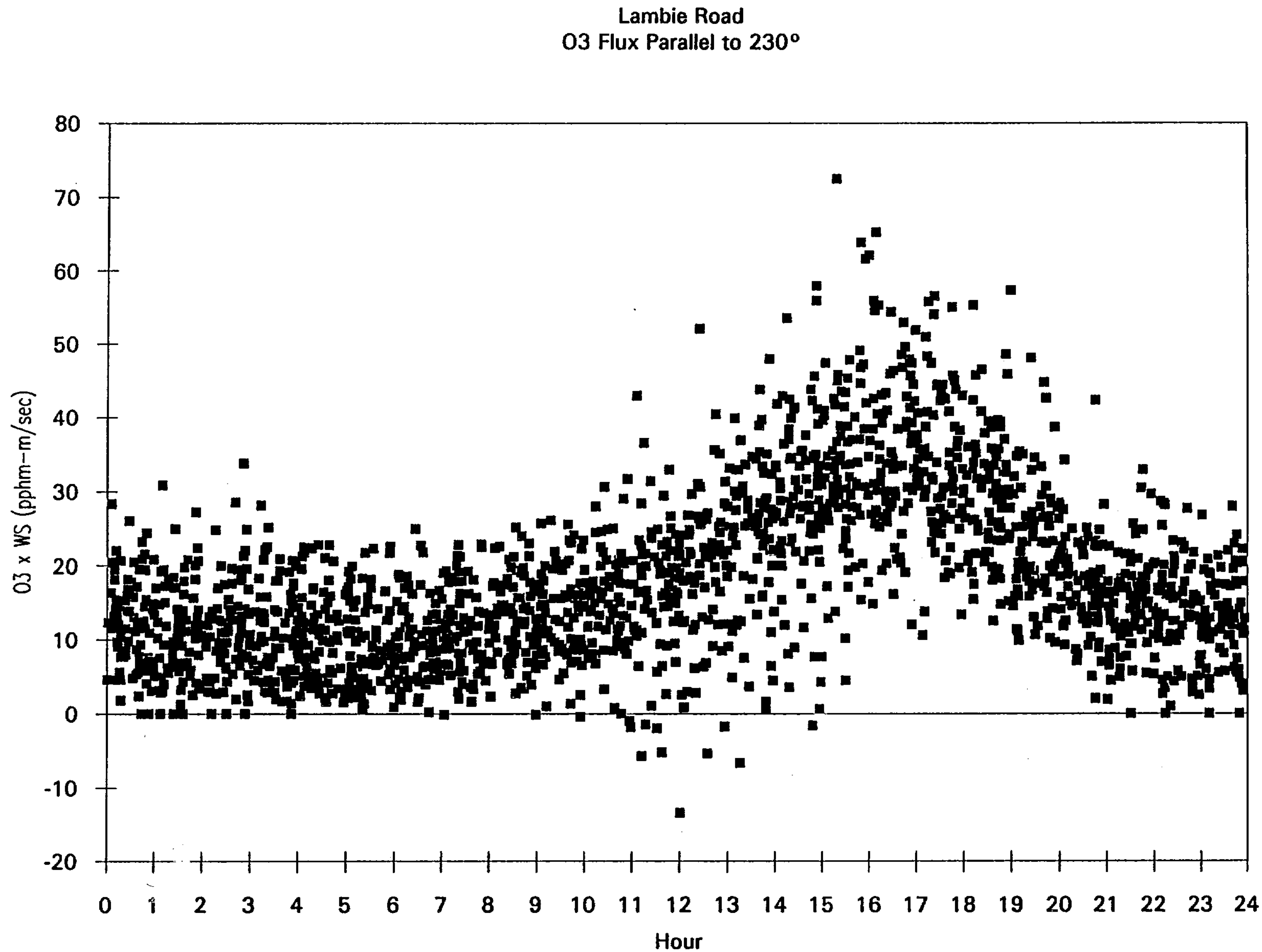


Figure 3-17. Estimated Relative Ozone Flux at Lambie Road, June 15 through September 15, 1990.

LAMO3HR.XLC

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The Lambie Road site is in a level area; typically afternoon wind speeds are very high in this area. The site is seldom influenced by the traffic on I-80. Thus the ozone concentrations measured there generally represent the mixed layer during the day and the nocturnal boundary layer at night.

During the June 15 to September 15, 1990 period, there were only about 12 hours of negative flux at Lambie Road; the rest of the time the winds carried pollutants from the SFBAAB into the Sacramento Valley at the surface. The relative flux in Figure 3-17 shows a very consistent diurnal pattern with an afternoon peak and relatively constant from about 2100 PDT until 1000 PDT. Day-specific relative ozone flux, hourly ozone concentration, and hourly resultant wind speed are shown for three summer 1990 periods in Figures 3-18 to 3-20. The dominant conclusion from these figures is the regular diurnal pattern of ozone peaks every afternoon, with corresponding relative ozone flux peaks at the same time. Wind speeds are also typically highest in the afternoon and on into the evening, but the ozone concentrations fall off by evening. July 10th is an exception: a very high ozone peak, but light winds with even a few hours of northeasterly winds in the middle of the day. However, this reverse flow at the surface did not last long enough to produce transport from the Sacramento Valley to the SFBAAB. The 1989 ozone and relative ozone flux results are similar to the results from the 1990 data illustrated here.

NO_x was also measured at the Lambie Road site during 1989 and 1990. Figure 3-21 shows the relative NO_x flux for the June 15 to September 15, 1990 period. This is much different than the ozone data. The relative NO_x flux varies quite a lot at all hours of the day, but the highest values occur in the evening through the early morning. Most of the values are between 0 and 100 ppb-m/s, but peak values range up to about 250 ppb-m/s; however, there are few values above 100 ppb-m/s during the daytime period of 1100 PDT to 1800 PDT. In fact, this is the time that the high ozone concentrations are being transported. Day-specific data for July 10-14 and August 2-3, 1990 is shown in Figures 3-22 and 3-23; note that the NO_x monitor died late on August 3rd. During the July period, the shape of the relative NO_x flux is similar to the shape of the NO_x concentration, with morning peaks in both. August 2-3 shows an additional pattern: another NO_x and relative NO_x flux peak in the late evening. These two peaks correspond to significant NO_x transport from the SFBAAB to the Sacramento Valley. Again, similar results were obtained using the summer 1989 NO_x and wind data at Lambie Road.

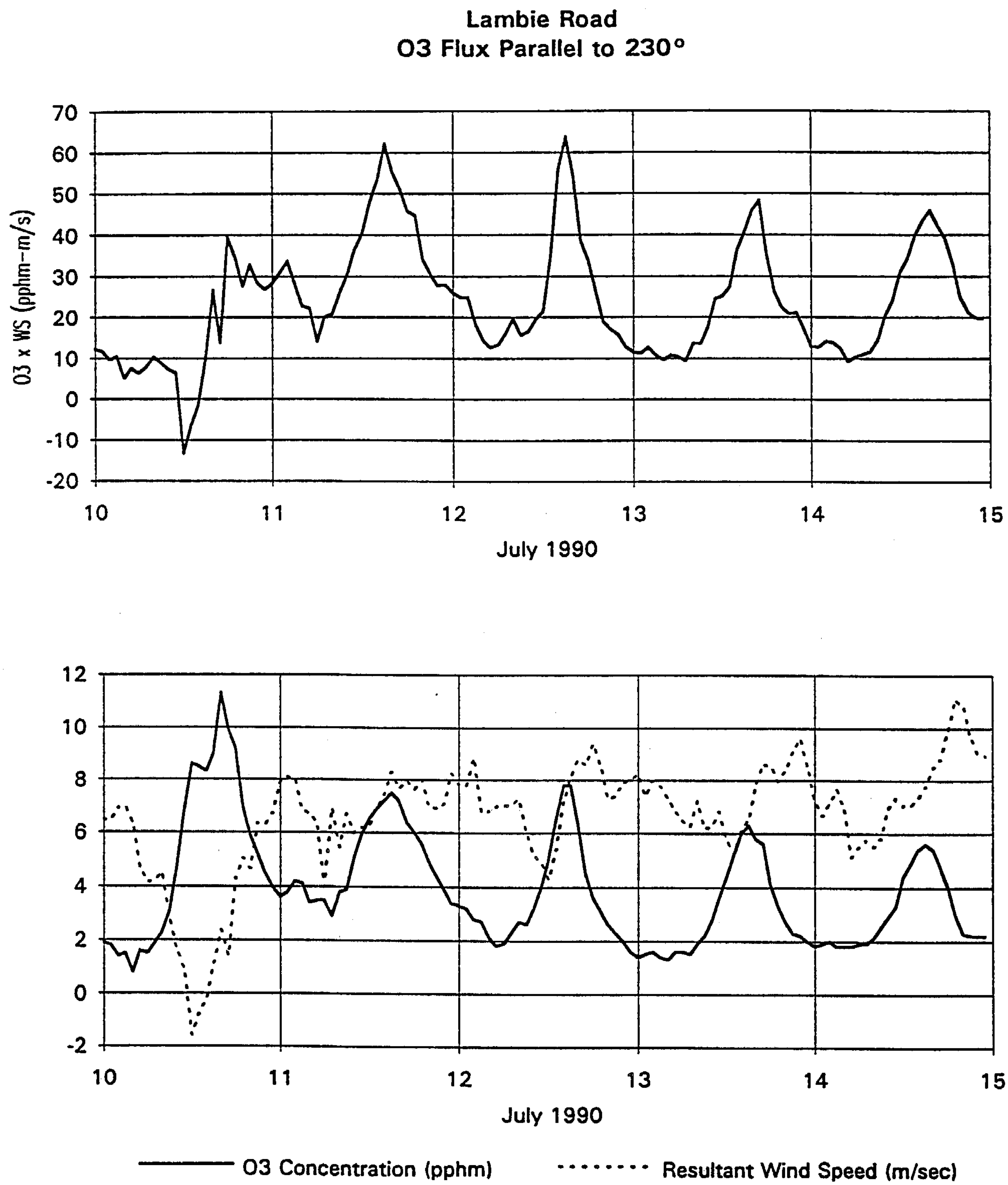

Figure 3-18. Estimated Relative Ozone Flux, Ozone Concentration, and Resultant Wind Speed at Lambie Road, July 10-14, 1990.

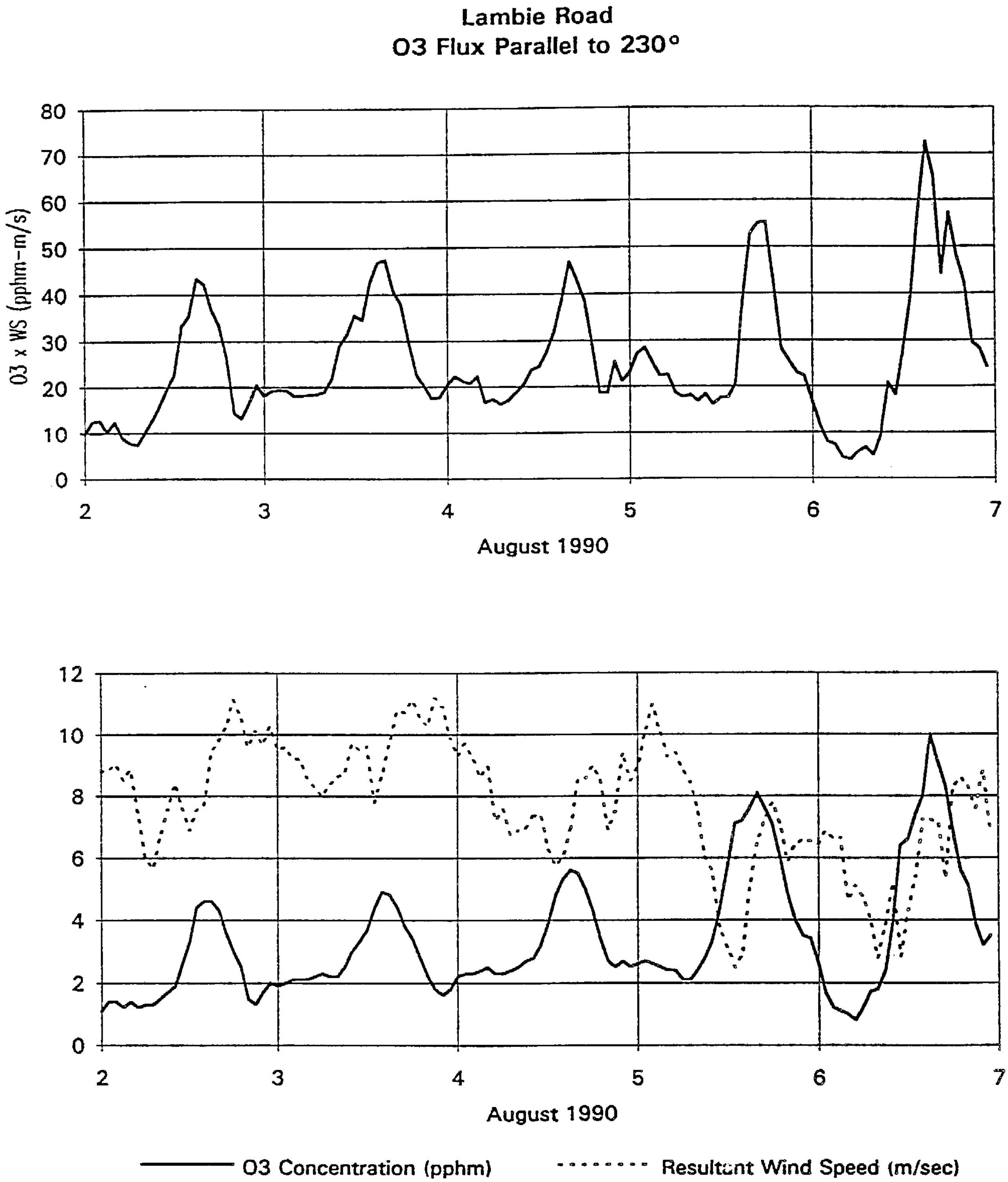

Figure 3-19. Estimated Relative Ozone Flux, Ozone Concentration, and Resultant Wind Speed at Lambie Road, August 2-6, 1990.

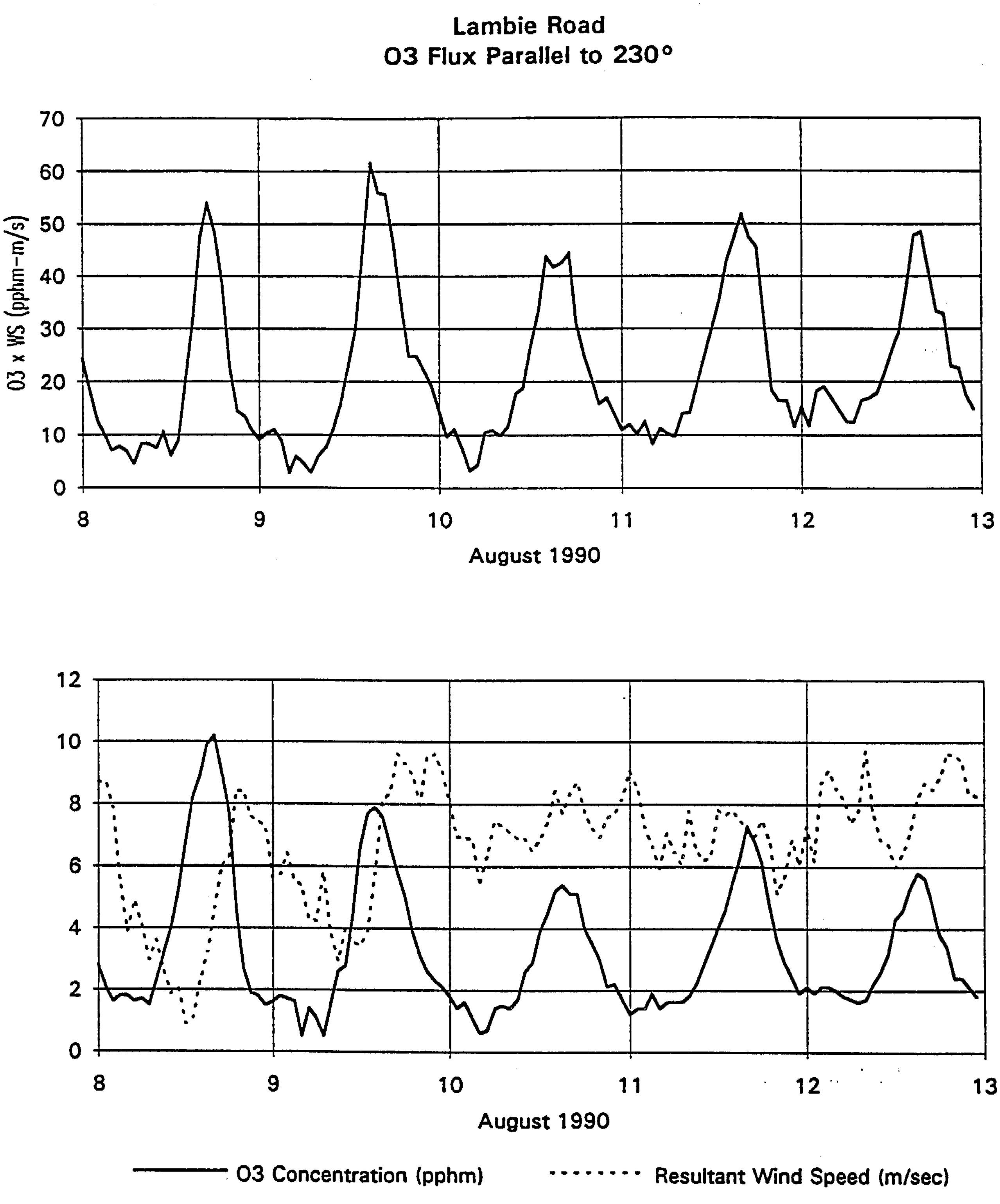

Figure 3-20. Estimated Relative Ozone Flux, Ozone Concentration, and Resultant Wind Speed at Lambie Road August 8-12, 1990.

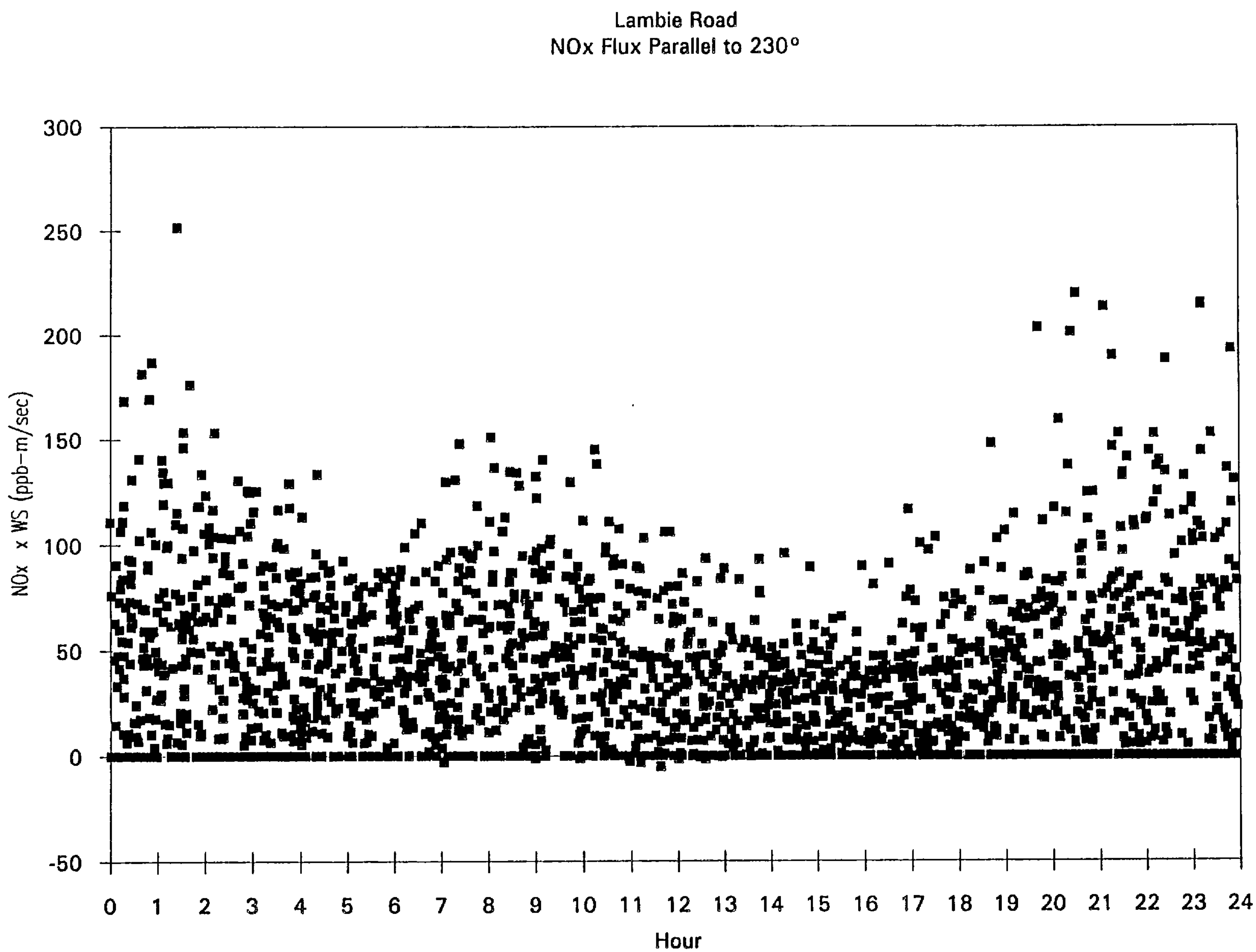

Figure 3-21. Estimated Relative NO_x Flux at Lambie Road, June 15 through September 15, 1990.

LAMNOXHR.XLC 9/20/91 11:49 AM

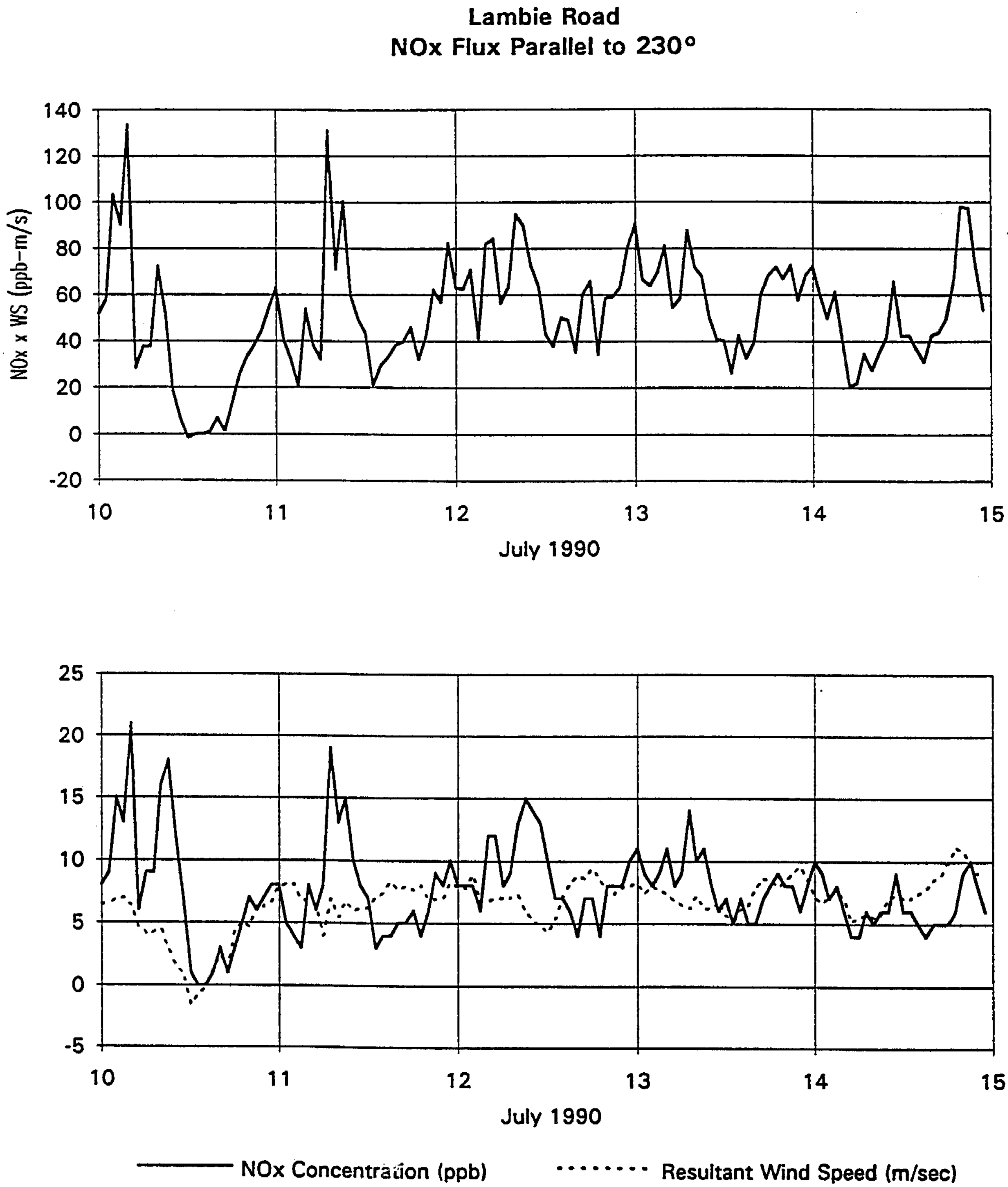

Figure 3-22. Estimated Relative NO_x Flux, NO_x Concentration, and Resultant Wind Speed at Lambie Road, July 10-14, 1990.

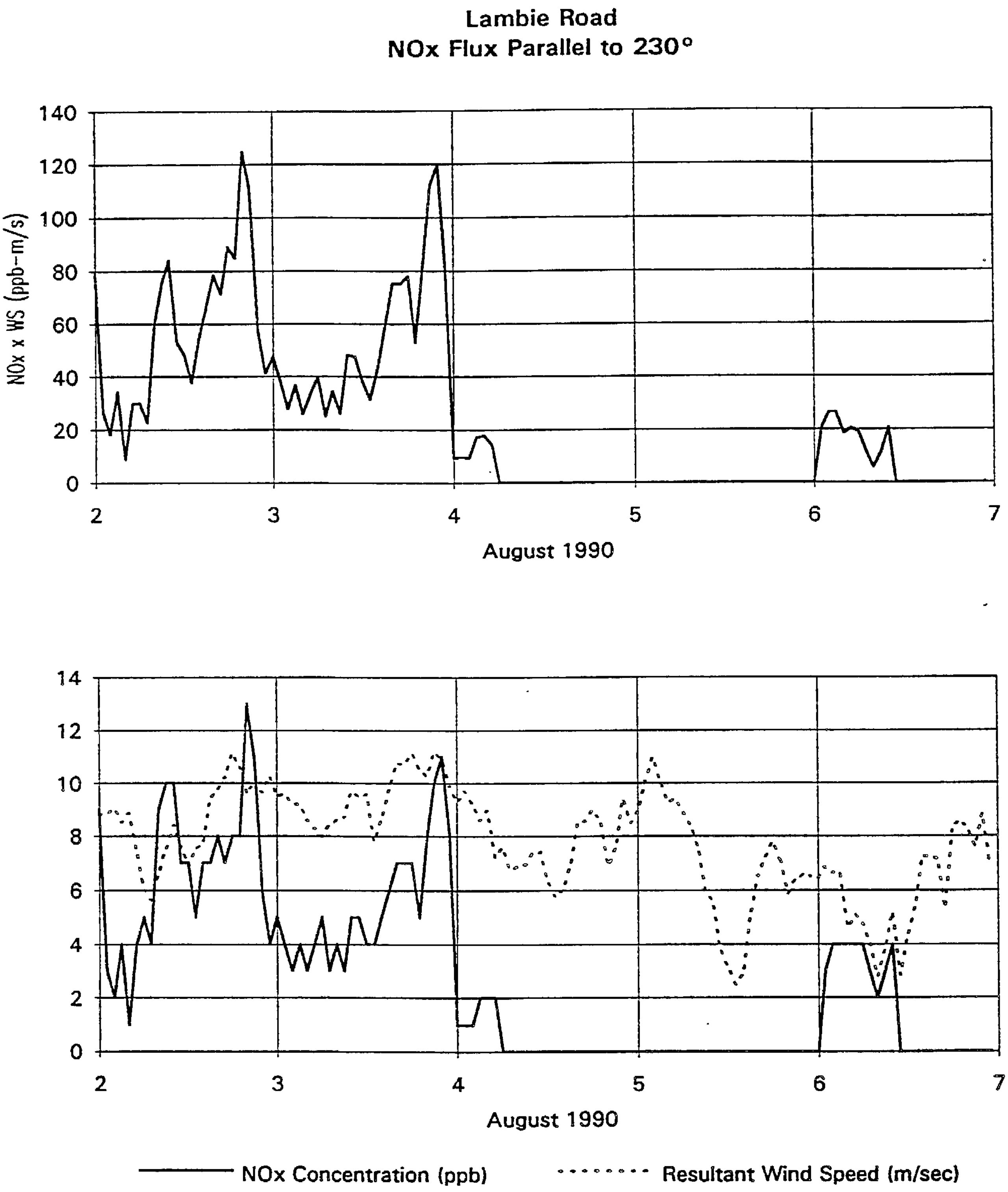

Figure 3-23. Estimated Relative NO_x Flux, NO_x Concentration, and Resultant Wind Speed at Lambie Road, August 2-6, 1990.